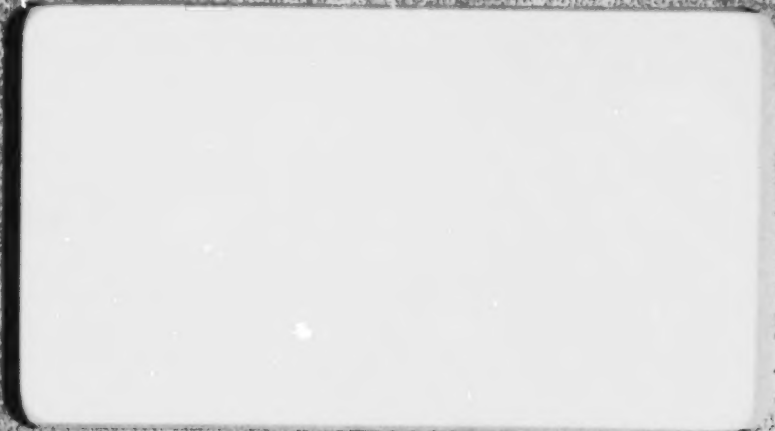




CA1
DTC 847
85
F27
c.2



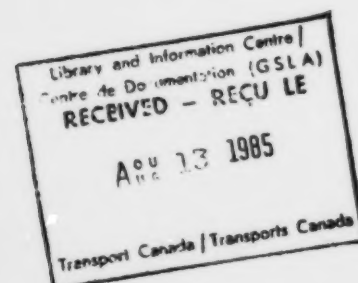
CANADIAN ASTROPHYSICAL OBSERVATORY

TP 6501E

FEASIBILITY STUDY
OF AN MLS GROUND CERTIFICATION AND
MEASUREMENT FACILITY

PREPARED FOR:
TRANSPORTATION
DEVELOPMENT CENTRE
BY: Canadian Astronautics Ltd.
1050 Morrison Drive.
Ottawa, Ontario

Date: May, 1985
Contract: DSS# 11SDT 8200-4-4557
Report: CAL # 340-FR-001



NOTE: The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre.

PROJECT TEAM

The project team for Canadian Astronautics Limited was composed of:

G. BOUDREAU

J. WHELPTON

D. M. BALL

And Others.

REPORT DOCUMENTATION FORM

1. Transport Canada Report No. TP 6501E	2. TDC Project No. 6331	3. Recipient's Catalogue No.	
4. Title and Subtitle Feasibility Study of an MLS Ground Certification and Measurement Facility		5. Report Date May, 1985	
		6. Performing Organization Report No. 340-FR-001	
7. Author(s) G. Boudreau, J. Whelpton, D.M. Ball		8. Transport Canada File No. D 1455-153	
9. Performing Organization Name and Address Canadian Astronautics Limited 1050 Morrison Drive Ottawa, Ontario K2H 8K7		10. DSS File No. 11SD T8200-4-4557	
		11. DSS or Transport Canada Contract No. OSD 84-00219	
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) Complexe Guy Favreau Suite 601, West Tower Montreal, Quebec H2Z 1X4		13. Type of Report and Period Covered Final - Dec. 84/May 85	
		14. Sponsoring Agency Code 6331	
15. Supplementary Notes		16. TDC Project Officer Micha Avni	
17. Abstract This report describes a ground-based Microwave Landing System (MLS) test facility, with the capability for performing tests before, during, and after installation of an MLS. MLS, which will become the prime aircraft landing system by 1995 (replacing the existing Instrument Landing System), will provide significantly enhanced performance, allowing aircraft to land in difficult terrain and under low visibility conditions. The system also provides dramatically increased coverage, making airborne testing difficult and expensive; ground-based testing is therefore preferred. The report describes alternative test techniques, providing advantage and disadvantages of each; then, based on analysis of performance and projected costs, defines an optimal test system. The airport test facility consists of a spatially matched receiving probe antenna mounted on a movable tower located 35 metres in front of the MLS, together with a van-mounted electronics subsystem and a probe antenna tracking unit. Potential multipath problem areas are identified by applying antenna sidelobe level test data obtained from a calibrated antenna test facility to the configuration of major multipath reflector sources at each airport. Included in the report are detailed descriptions of a first article MLS antenna test facility, a commissioning test facility, and a periodic test facility.			
18. Key Words Microwave Landing System Air Traffic Control Navigation Testing		19. Distribution Statement Limited number of copies available from TDC	
20. Security Classification (of this report) Unclassified	21. Security Classification (of this page) Unclassified	22. No. of Pages 218	23. Price NIL

FORMULE DE DOCUMENTATION POUR RAPPORT

1. N° du rapport Transports Canada TP 6501E	2. N° de l'étude — CDT 6331	3. N° de catalogue du destinataire	
4. Titre et sous-titre Feasibility Study of an MLS Ground Certification and Measurement Facility		5. Date du rapport Mai 1985	
		6. N° du rapport de l'organisme exécutant 340-FR-001	
7. Auteur(s) G. Boudreau, J. Whelpton, D.M. Ball		8. N° de dossier Transports Canada D 1455-153	
9. Nom et adresse de l'organisme exécutant Canadian Astronautics Limited 1050 Morrison Drive Ottawa, Ontario K2H 8K7		10. N° de dossier — ASC 11SD T8200-4-4557	
		11. N° de contrat — ASC ou Transports Canada OSD 84-00219	
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) Complexe Guy Favreau Suite 601, tour ouest Montréal, Québec H2Z 1X4		13. Genre de rapport et période visée Final, déc. 84 - mai 85	
		14. Code de l'organisme parrain 6331	
15. Remarques additionnelles		16. Agent de projet — CDT Micha Avni	
17. Resume Ce rapport décrit une installation d'essai au sol de systèmes d'atterrissage hyperfréquences (MLS) pouvant tester un MLS avant, pendant et après son installation. Le MLS, qui sera le principal système d'atterrissage utilisé en 1995 (en remplacement de l'actuel système d'atterrissage aux instruments), est beaucoup plus efficace et permet aux aéronefs d'atterrir sur des terrains difficiles et dans des conditions de faible visibilité. Ce système a aussi une couverture beaucoup plus étendue, ce qui rend les essais en vol difficiles et coûteux; c'est la raison pour laquelle un système d'essai au sol a été choisi. Le rapport décrit plusieurs méthodes d'essai en indiquant les avantages et les inconvénients de chacune; puis, en se basant sur une analyse de performance et de coûts prévus, il définit les caractéristiques d'un système d'essai optimal. L'installation d'essai est constituée d'une antenne réceptrice de sondage adaptée à la configuration de l'emplacement et montée sur une tour mobile à 35 mètres devant le MLS, ainsi que d'un sous-système électronique et d'une unité de poursuite montés dans une remorque. Les problèmes potentiels dus aux trajets multiples sont identifiés en appliquant à la configuration des principales sources de trajets multiples à chaque aéroport les données obtenues, au moyen d'une antenne étalonnée, pour les lobes latéraux. Le rapport donne une description détaillée de trois installations: la première sert à faire l'essai de la première antenne MLS livrée, la deuxième sert aux épreuves de mise en service et la troisième aux vérifications périodiques.			
18. Mots-clés Système d'atterrissage hyperfréquences Contrôle de la circulation aérienne Navigation Essai		19. Diffusion Le CDT dispose d'un nombre limité d'exemplaires	
20. Classification de sécurité (de ce rapport) non classifié	21. Classification de sécurité (de cette page) non classifiée	22. Nombre de pages 218	23. Prix -

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the advice and assistance provided by Transport Canada, in particular, Mr. J. Hastie.

TABLE OF CONTENTS

	<u>Page</u>
1.0 EXECUTIVE SUMMARY	1-1
2.0 INTRODUCTION	2-2
3.0 ANALYSIS OF REQUIREMENT	3-1
3.1 INTRODUCTION	3-1
3.2 REQUIREMENT	3-1
3.2.1 SITE CHARACTERISTICS	3-1
3.2.2 RF CARRIER	3-2
3.2.3 MLS COVERAGE REGIONS	3-3
3.2.4 SIGNAL TYPES AND CHARACTERISTICS	3-3
3.2.5 TIME DOMAIN MULTIPLEX	3-10
3.2.6 SYSTEM ACCURACY	3-30
3.2.7 MONITOR AND CONTROL REQUIREMENTS	3-30
3.3 ENVIRONMENTAL REQUIREMENTS	3-36
3.4 COMMENTS ON THE ICAO SARP	3-38
3.4.1 POSSIBLE AMENDMENTS TO THE SARP	3-38
3.4.2 FUNCTION TIMING REQUIREMENTS	3-38
4.0 STUDY OF MEASUREMENT TECHNIQUES	4-1
4.1 SPATIALLY INVARIANT PARAMETERS	4-1
4.1.1 RECEIVING SYSTEM CONFIGURATIONS	4-3
4.1.2 SPATIALLY VARIANT PARAMETERS	4-17
4.1.3 OTHER POSSIBLE IMPLEMENTATIONS	4-13
4.1.4 TEST FACILITY HARDWARE	4-20
4.2 RADIATED SIGNAL PARAMETERS	4-30
4.2.1 RADIATION PATTERNS	4-30
4.2.2 ANTENNA REQUIREMENTS	4-35
4.2.3 RECEIVING ANGLE PROCESSOR	4-47
4.2.4 MULTIPATH MEASUREMENTS	4-71
4.3 ENVIRONMENTAL SENSITIVITY OF MLS ANTENNA	4-85
4.3.1 TEMPERATURE SENSITIVITY	4-87
4.3.2 HUMIDITY SENSITIVITY	4-91
4.3.3 RAIN AND ICE	4-91
4.3.4 VIBRATION	4-99

TABLE OF CONTENTS (Continued)

	<u>Page</u>
5.0 TEST FACILITY DESCRIPTION	5-1
5.1 FIRST ARTICLE ANTENNA TEST FACILITY	5-1
5.1.1 TEST PARAMETERS	5-2
5.1.2 FAMAT FACILITY DESCRIPTION	5-2
5.1.3 SIDELobe LEVEL MEASUREMENT	5-6
5.1.4 ENVIRONMENTAL TESTS	5-12
5.1.5 SOFT FAILURE TESTING	5-14
5.2 COMMISSIONING TEST FACILITY	5-15
5.2.1 ANTENNA SUBSYSTEM	5-15
5.2.2 RECEIVER/PROCESSOR SUBSYSTEM	5-28
5.2.3 MULTIPATH MEASUREMENT	5-35
5.2.4 ESTIMATED COSTS OF A CTF	5-36
5.2.5 OPTIONAL FEATURES	5-39
5.3 PERIODIC TEST FACILITY	5-40
5.3.1 TEST PHILOSOPHY	5-41
5.3.2 ANTENNA SUBSYSTEM	5-41
5.3.3 RECEIVER/PROCESSOR	5-42
5.3.4 ESTIMATED COSTS	5-43
6.0 CONCLUSIONS AND RECOMMENDATIONS	6-1
6.1 MLS DESIGN REQUIREMENTS	6-1
6.2 FAMAT FACILITY	6-3
6.3 COMMISSIONING TEST FACILITY	6-5
6.4 PERIODIC TEST FACILITY	6-8
7.0 REFERENCES	7-1
 APPENDIX A	 A-1
APPENDIX B	B-1
APPENDIX C	C-1
APPENDIX D	D-1

LIST OF ILLUSTRATIONS

	<u>Page</u>
Figure 2.1 MLS Radiated Signal Zones	2-2
Figure 2.2 Azimuth/Elevation Coverage, 2 Fan-Shaped Beams	2-4
Figure 3.1 Approach Azimuth Coverage	3-5
Figure 3.2 Back Azimuth Coverage	3-7
Figure 3.3 Approach Elevation Coverage	3-9
Figure 3.4 Clearance Pulse Conventions for Azimuth Functions	3-13
Figure 3.5 Scanning Conventions for Azimuth Guidance Functions	3-14
Figure 3.6 Scanning Conventions for Approach Elevation and Flare Guidance Functions	3-15
Figure 3.7 Far Field Dynamic Signal-in-Space	3-16
Figure 3.8 Power Density Requirements for Various Antenna Beamwidths	3-17
Figure 3.9 Angle Function Organization	3-27
Figure 3.10 Angle Scan Timing Parameters	3-28
Figure 3.11 Complete Multiplex Transmission Cycle Showing Open Time Periods Available For Data Words	3-29
Figure 4.1 Test Configuration A	4-4
Figure 4.2 Test Configuration B	4-5
Figure 4.3 DPSK Demodulator	4-8
Figure 4.4 Frequency Locking Circuit	4-12
Figure 4.5 Shift Register Implementation of Trigger and Function Decoder	4-14
Figure 4.7 Digitized Signals	4-19
Figure 4.8 A Laser-Based Near Field Measurement System	4-33
Figure 4.9 Far Field/Near Field Comparison on Boresight	4-36
Figure 4.10 Pattern 30° Off-Boresight	4-37
Figure 4.11 Pattern 60° Off-Boresight	4-38
Figure 4.12 Beam Squint for Quasi-Near Field Distance	4-39
Figure 4.13 Point Source as Probe Antenna	4-40
Figure 4.14 Interferometer Antenna at 38 Meters Distance	4-47
Figure 4.15 MLS Receiver Waveforms	4-49
Figure 4.16 Centroid Method	4-51
Figure 4.17 Analog Centroid Method	4-52
Figure 4.18 Iterative Process	4-55

LIST OF ILLUSTRATIONS (Continued)

	<u>Page</u>
Figure 4.19 Correlation Method	4-56
Figure 4.20 Weighted Prediction of Beam Center	4-59
Figure 4.21 Training Run Implementation	4-62
Figure 4.22 Transversal Filter Implementation of LMS Algorithm	4-65
Figure 4.23 Threshold Quantization	4-67
Figure 4.24a Multipath Caused by Scan Plane Sidelobes (AZ System)	4-73
Figure 4.24b Multipath Caused by Scan Plan Sidelobes (EL System)	4-73
Figure 4.24c Multipath Caused by Non-Scan Plane Sidelobes (AZ System)	4-73
Figure 4.25a Azimuth PFE/CMN Variation with Approach Angle	4-74
Figure 4.25b Elevation PFE/CMN Variation with Approach Angle	4-74
Figure 4.26 Sidelobe Level for Azimuth System	4-79
Figure 4.27 Sidelobe Level for Elevation System	4-80
Figure 4.28 Ground Reflection Measurements	4-83
Figure 4.29 Array Model	4-88
Figure 4.30 Perturbation Model	4-88
Figure 4.31 Transmission Efficiency ($\epsilon=4.2$)	4-92
Figure 4.32 Transmission Efficiency ($\epsilon=4.2$)	4-93
Figure 4.33 Transmission Efficiency ($\epsilon=9$)	4-95
Figure 4.34 Transmission Efficiency ($\epsilon=9$)	4-96
Figure 4.35 Beam Squint Due by Refraction	4-97
Figure 4.36 Increase in Sidelobe Level Due to Random Phase Errors	4-101
Figure 5.1 First Article Antenna Test Facility	5-3
Figure 5.2 Sidelobe Level Definition	5-7
Figure 5.3 FAA Sidelobe Level Measuring Approach	5-10
Figure 5.4 FAA SLL Test Waveshapes	5-11
Figure 5.5 Commissioning Test Measurement Zone	5-16
Figure 5.6 Suggested Antenna Mounting Techniques	5-18
Figure 5.7 45 cm. Array Pattern	5-22
Figure 5.8 75 cm. Array Pattern	5-23
Figure 5.9 120 cm. Array Pattern	5-24
Figure 5.10 Use of Diffraction Fence to Block Reflections	5-25
Figure 5.11 Commissioning Test Set	5-29
Figure B.1 Quasi-Near Field Model	B-2
Figure B.2 Far-Field Model	3-3

LIST OF TABLES

	<u>Page</u>
Table 3-1 Approach Azimuth Coverage	3-4
Table 3-2 Back Azimuth Coverage	3-6
Table 3-3 Elevation Coverage (Proportional)	3-8
Table 3.4 Signal Specifications	3-11
Table 3.5 Scanning Function Specifications	3-12
Table 3.6 Function Rates	3-18
Table 3.7 Morse Code Timing	3-19
Table 3.8	3-21
Table 3.9 Approach Elevation Function Timing	3-22
Table 3.10 High Rate Approach Azimuth and Back Azimuth Function Timing	3-22
Table 3.11 Basic Data Function Timing	3-23
Table 3.12 Auxiliary Data Function Timing	3-23
Table 3.13 Preamble Timing	3-24
Table 3.14 Function Code	3-25
Table 3.15 System Guidance Accuracies at Reference Datum ($\pm$ Degrees)	3-31
Table 3.16 Azimuth Accuracy ($\pm$ Degrees) Limits	3-32
Table 3.17 System Back Azimuth Accuracy Limits ($\pm$ Degrees)	3-33
Table 3.18 System Elevation Accuracy Limits ($\pm$ Degrees)	3-34
Table 3.19 Ground Equipment Accuracy Limits ($\pm$ Degrees)	3-35
Table 3.20 Interrelationship of Ground Equipment Monitor and Control Action	3-36
Table 3.21	3-37
Table 4.1 SIP's	4-2
Table 4.2 Downconverter	4-21
Table 4.3 Demodulators	4-22
Table 4.4 Amplitude Detector	4-23
Table 4.5 Frequency Counters	4-24
Table 4.6 Logic State Analyzers	4-25
Table 4.7 Time Interval Measurement	4-26
Table 4.8 Phase Measurement	4-27
Table 4.9 Power Meters	4-28
Table 4.10 Spectrum Analyzer	4-29
Table 4.11	4-69
Table 4-12 Multipath Error Component	4-76
Table 4-13a Required Effective Sidelobe Levels (CMN Limits)	4-77
Table 4-13b FAA ESL Requirements	4-77
Table 4.14	4-81
Table 4.15	4-90
Table 4-16	4-94
Table 5.1 Recurring Costs	5-38
Table 5.2 Option B Module Costs	5-38

1.0 EXECUTIVE SUMMARY

The MLS Ground Test Facilities Study Report describes a ground-based Microwave Landing System (MLS) test facility, which includes a capability for performing tests before, during, and after installation of a MLS. MLS, which will become the prime landing system by 1995 (replacing the existing Instrument Landing System), will provide significantly enhanced performance, allowing aircraft to land in difficult terrain and under low visibility conditions. The system also provides dramatically increased coverage area, which makes airborne testing difficult and expensive, therefore ground-based testing is preferred.

The report describes alternative test techniques, providing advantages and disadvantages of each, then defines the optimum test system based on an analysis of performance and projected costs.

The report includes a detailed description of three uniquely definable test systems which encompass before, during and after installation testing requirements, i.e.:

a) First Article MLS Antenna Test Facility

This facility is needed to supplement factory testing of the MLS, particularly relating to measurement of antenna performance, both sidelobe level tests and testing the environmental sensitivity of the MLS antenna. A calibrated, low multipath antenna test range is described in this section.

b) Commissioning Test Facility

This facility is necessary to test the MLS upon completion of a new installation. The facility includes a van equipped with a combination of commercial and custom electronics equipment, an erectable tower with a 45 cm. square slotted waveguide array antenna, and an antenna tracking subsystem.

c) Periodic Test Facility

This facility is needed to periodically verify that the MLS is performing to specification and that performance is not gradually degrading as well as confirming that the MLS field monitor is functioning correctly.

This facility is electronically similar to the Commissioning Test Facility except that the electronics unit is smaller, the antenna tower is fixed and the antenna tracker is not needed.

2.0 INTRODUCTION

This report describes the results of an Microwave Landing System (MLS) Ground Test Facility Study, the purpose of which was to determine the feasibility of a ground-based MLS test facility and to define in detail the characteristics of such a test facility.

The MLS is scheduled to become the prime aircraft landing system by 1995, replacing the present International Civil Aviation Organization (ICAO) standard VHF/UHF instrument landing system (ILS). MLS will provide greater accuracy and will extend flyable guidance over wider areas of coverage (up to 120° in azimuth and 20° in elevation) with much greater freedom from the effects of terrain irregularities and adverse weather conditions than with ILS. Figure 2.1 illustrates in a graphical form the coverage provided by the MLS.

Because of its versatility, autoland accuracy, reduced installation costs and lower maintenance requirements, MLS will provide a greater capability than ILS to establish precision approaches when required, and will, therefore, provide important improvements in air transportation safety and efficiency. By allowing more direct landing approaches, under all weather conditions, aircraft fuel consumption could be reduced dramatically. Furthermore, the approach assistance provided by this system would facilitate helicopter or STOL aircraft landings during periods of low visibility.

The enhanced performance of the MLS will permit landings over difficult terrain and/or under low visibility conditions and, as a consequence, aircraft will become more and more dependent on these systems. This dependency will make it increasingly important that the accuracy is provided and maintained over the system lifetime. The study examined in great detail alternative techniques of certifying and calibrating the MLS before, during and after installation, with the objective of defining a cost effective technique of confirming operation under a wide variety of Canadian operating conditions using a ground based test system.

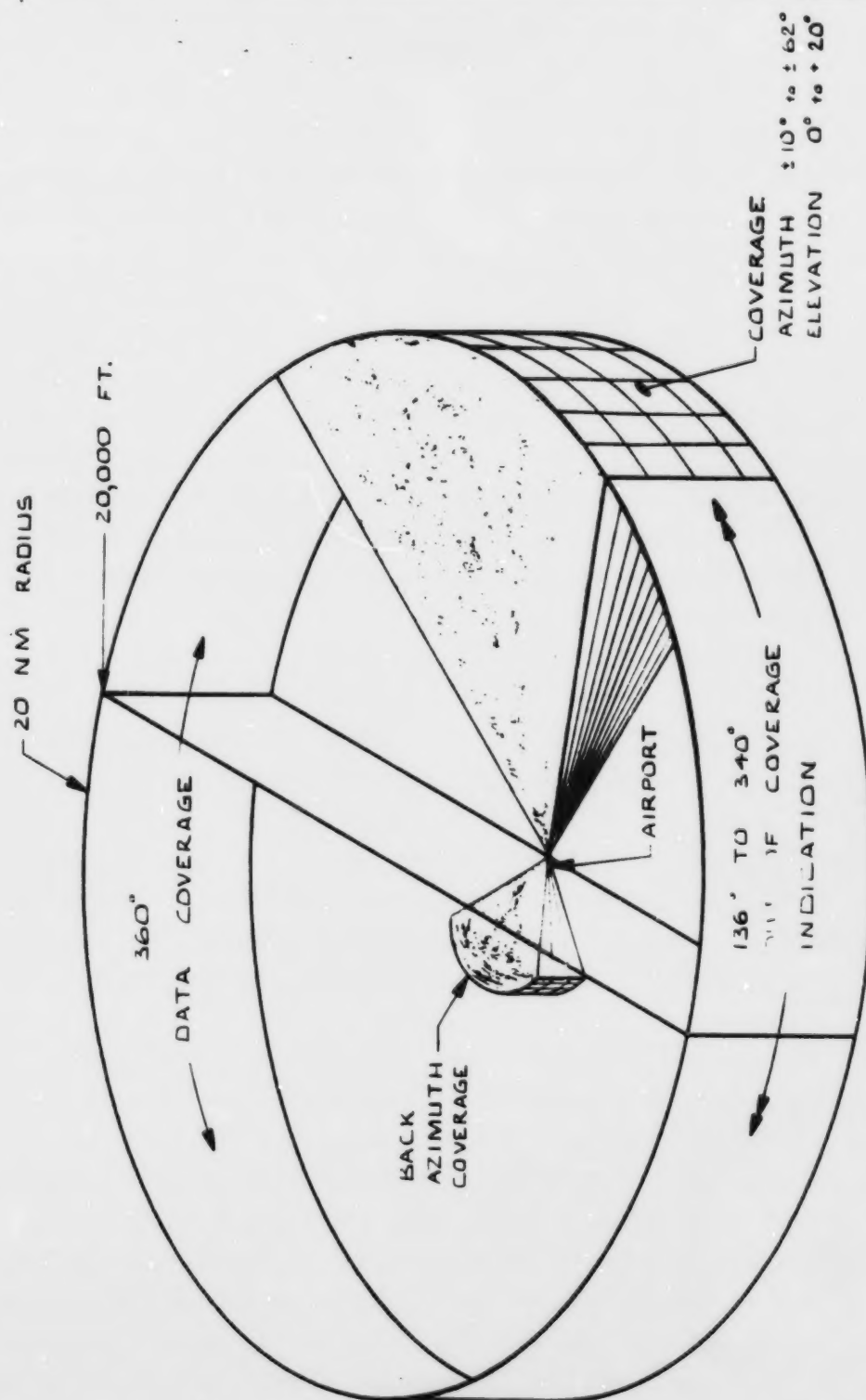


Figure 2.1 MLS Radiated Signal Zones

Figure 2.2 is provided to illustrate the MLS technique which was selected to provide reliable, accurate position location in two dimensions over an extremely wide coverage area. The technique involves generation of two very narrow fan-shaped beams, one of which scans to the right and left (TO/FRO) and the other, up and down. The operating principle is based on the right/left and up/down scanning rate being very carefully controlled so that the aircraft receiver must only measure the time taken from receipt of the TO scan to receive of the FRO scan to know precisely its location in azimuth, and then repeating the time test on the Up/Down scan to find its location in elevation. When this information is coupled with range information supplied by a co-located precision distance measuring equipment (DME-P), the aircraft position is now known in three dimensional space.

The study examines the problem of testing the MLS by first analyzing the ICAO requirements in some detail. The results of this analysis is contained in Section 3 of the report. Having defined the test parameters and performance limits, several alternative measurement techniques were explored and discussed in great detail in Section 4 of the report. Considerable effort was spent on defining alternative equipment for parameter measurements with the advantages and disadvantages of each being defined.

The optimum system was selected from the alternative approaches considering factors such as accuracy, ease of use, cost effectiveness, etc. Three test systems were defined in Section 5, i.e.:

- First Article MLS Antenna Test Facility
- Commissioning Test Facility
- Periodic Test Facility

Each of these facilities was defined essentially to meet the need for testing a MLS before, during and after installation. Although the measurement equipment was similar for each case, specific differences have been highlighted.

Section 6 of the report summarizes all of the recommendations and conclusions in one section for easy reference.

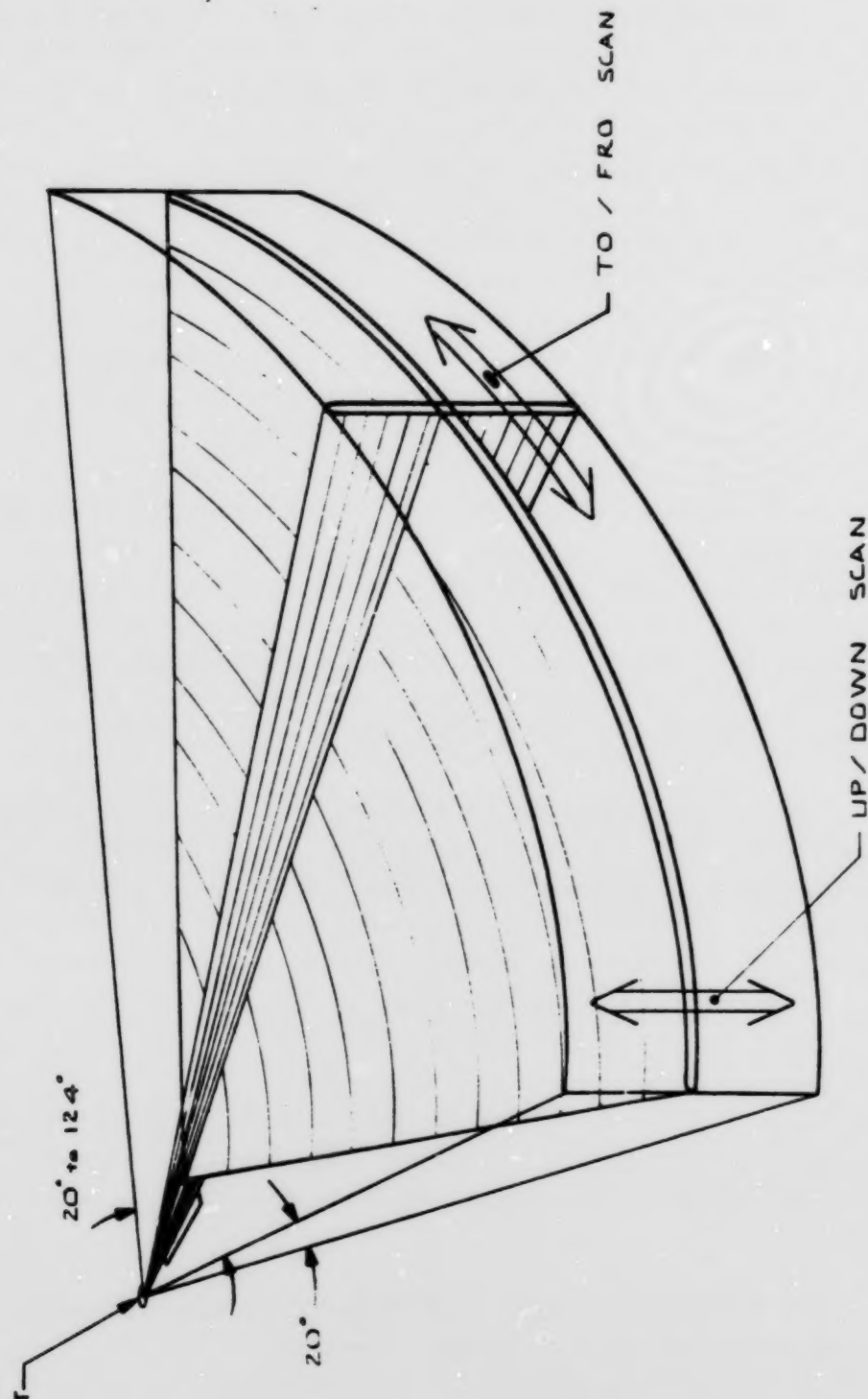


Figure 2.2 Azimuth/Elevation Coverage, 2 Fan-Shaped Beams

3.0 ANALYSIS OF REQUIREMENT

3.1 INTRODUCTION

MLS is a precision approach landing guidance system which provides position information by means of azimuth angle, elevation angle and distance measurement. [ICAO para. 3.11.2] (Ref. 1)

For the purpose of this study, the MLS configuration consists of:
[ICAO para. 3.11.3]

- a) approach azimuth equipment
- b) back azimuth equipment
- c) elevation equipment
- d) means of transmitting and encoding data words
- e) associated monitor for each of the above functions

The Flare function and the DME-P function have been excluded from this study at the request of the Scientific Authority.

This section of the report provides a summary of the ICAO requirements for the MLS system and provides notes and comments on specific requirements of the ICAO specifications where the specification requires clarification or interpretation.

3.2 REQUIREMENT

3.2.1 SITE CHARACTERISTICS

- For the purpose of this study, it has been assumed that 95% of all sites have a runway length of 10,000 ft. (3048 m) or less, and the maximum runway length is 13,000 ft. (3963 m).
- The distance of the approach azimuth antenna to the runway stopend assumed to be 1,000 ft. (304.9 m).
- The minimum glide path (MGP) shall vary between 2.5° and 9° (nominally 3°), therefore, the maximum distance from the MLS datum point to threshold will be 1,145 ft. (343.6 m).

3.2.2 RF CARRIER REQUIREMENTS

- (i) Carrier Frequency: one of [ICAO para. 3.11.4.1.1]
 $5031.0 + 0.3 n$ (MHz)
 $n = 0, 1, 2, \dots, 199$
- corresponding channel #: $500 + n$
- (ii) Channel width: 300 kHz [ICAO para. 3.11.4.1.1]
- (iii) Frequency tolerance of carrier: [ICAO para. 3.11.4.1.3]
 ± 10 kHz
- (iv) Frequency stability: [ICAO para. 3.11.4.1.3]
 ± 50 Hz over a 1 sec. interval
- (v) RF signal spectrum (out of band): [ICAO para. 3.11.4.1.4]

Guidance	Height	Mean Power Density
Angle	> 600 m	< -100.5 dBW/M ²
Data	> 600 m	< -95.5 dBW/M ²

- measured in a 150 kHz BW centered 840 kHz or more from nominal frequency.
- NOTE: DOC acceptance criteria requires that out of band interference be less than 60dB below the in band carrier.

- (vi) Polarization: [ICAO para. 3.11.4.2]
 - All RF transmissions are nominally vertically polarized.
 - Effect of any horizontally polarized component shall not cause:
 - a) Guidance information to change by more than 40% of PFE allowed with airborne antenna rotated 30° from vertical position.
 - b) PFE limit to be exceeded with airborne antenna related 30° from the vertical position.

NOTE: The above is the recommended interpretation of the wording of ICAO para. 3.11.4.2.

(vii) Residual Radiation: [ICAO para. 3.11.5.1.1]

- a) At least 70 dB below level provided when transmitting, (for any MLS function), at times when another MLS is transmitting.
 - Acceptable level of residual radiation will have no adverse affect on the reception of any other MLS function.

3.2.3 MLS COVERAGE REGIONS

The coverage areas for the approach azimuth (AZ), high rate approach azimuth (HAZ), back azimuth (BAZ) and elevation (EL) functions are tabulated in Tables 3-1, 3-2, 3-3 and are illustrated in Figures 3-1, 3-2 and 3-3 respectively.

3.2.4 SIGNAL TYPES AND CHARACTERISTICS

MLS signalling is composed of four basic types of signals:

- a) DPSK modulated data
- b) To and FRO scanning beams
- c) OCI pulses
- d) clearance pulses

The characteristics and specifications of the DPSK, OCI and clearance pulses are summarized in Table 3.4.

Factors to note include:

- (i) Clearance pulses are used to supplement proportional coverage when it is less than the required coverage area. ($\pm 40^\circ$)
[ICAO para. 3.11.4.6.2.5]
- (ii) Two clearance pulse formats are possible: [ICAO para. 3.11.4.6.2.5 and para. 3.11.4.6.2.5.1]
 - a) Scanning beam can scan past limits of proportional coverage
 - if angle exceeds designated coverage, a fly left or right condition is indicated.

Table 3-1 Approach Azimuth Coverage [ICAO para. 3.11.5.2.2.1]

	Approach Region ICAO para. 3.11.5.2.2.1.1	Runway Region ICAO para. 3.11.5.2.2.1.2
Horizontal Limits		
(i) Lateral boundaries or sector angle	$\pm 40^\circ$ about ERCL (minimum proportional coverage is $\pm 10^\circ$)	45 meters (150') each side of runway center line
(ii) Near approach boundary or sector origin	MLS datum point	Runway stop end
(iii) Far approach boundary	37 km (20 NMi) from threshold	Approach region
Vertical Limits		
a) Lower limit		
(i) Surface type	Conical	Horizontal
(ii) Inclination Above horizontal	0.9°	0°
(iii) Origin	Vertically above threshold which is 2.5 m above farthest point on RCL in antenna line of sight	2.5 meters above farthest point on RCL in antenna line of sight
b) Upper limit		
(i) Surface type	Conical	Conical
(ii) Inclination Above horizontal	15°	20° (Recommended: 30°)
(iii) Origin	Azimuth antenna	Azimuth antenna
(iv) Maximum height	6,000 meters (20,000')	600 meters (2,000')

RCL=Runway Center Line

ERCL=Extended Runway Center Line

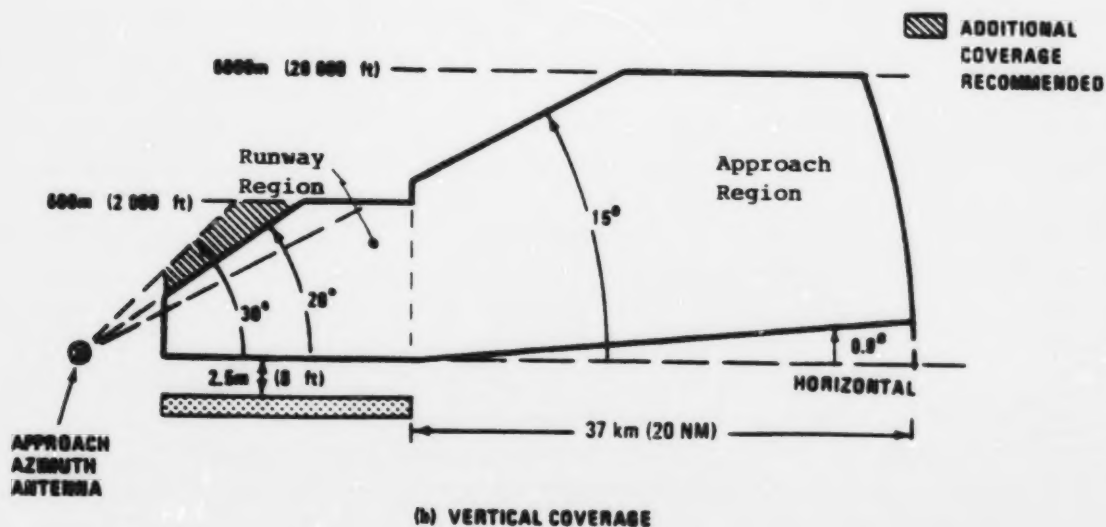
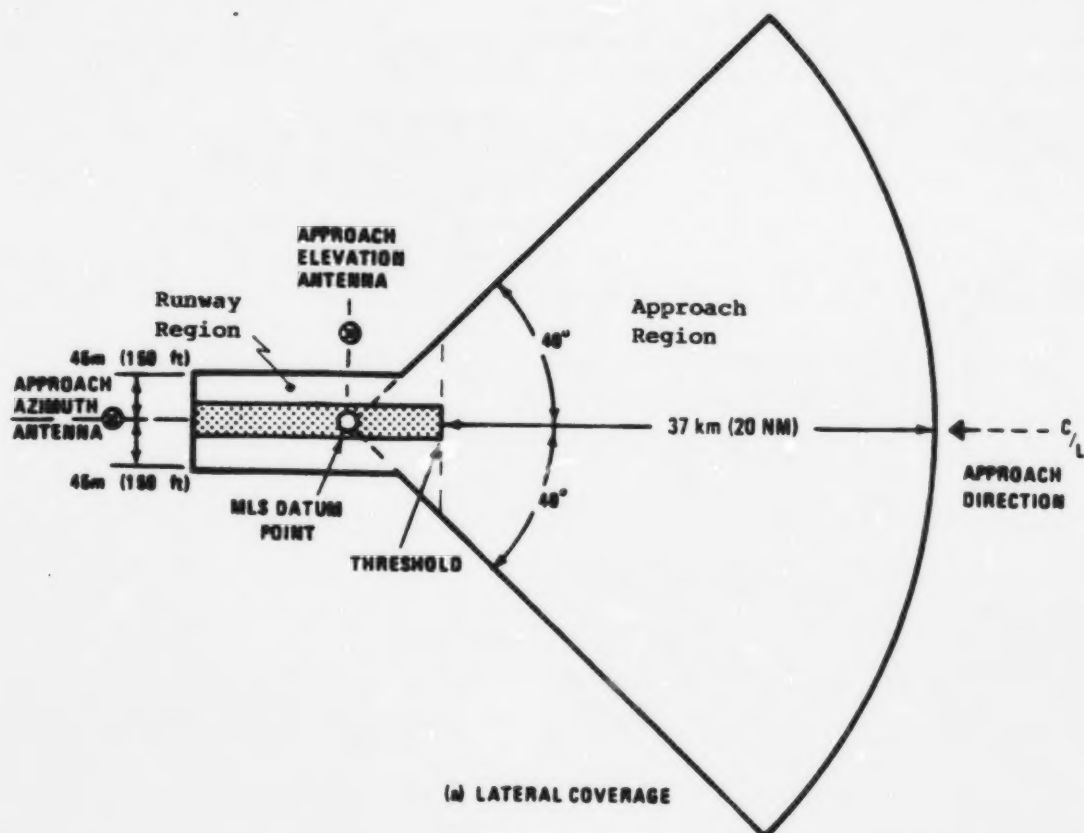


Figure 3.1 Approach Azimuth Coverage

Table 3-2 Back Azimuth Coverage [ICAO para. 3.11.5.2.2.2]

	Approach Region	Runway Region
Horizontal Limits		
(i) Lateral boundaries or sector angle	$\pm 20^\circ$ about ERCL (minimum proportional coverage is $\pm 10^\circ$)	Included in back azimuth region
(ii) Near approach boundary or sector origin	Back azimuth antenna	As above
(iii) Far approach boundary	9.3 km (5 NM) from runway stopend	As above
Vertical Limits		
a) Lower limit		
(i) Surface type	Conical	Horizontal
(ii) Inclination Above horizontal	0.9°	0°
(iii) Origin	2.5 meters above runway stopend	2.5 meters above farthest point on RCL in antenna line of sight
b) Upper limit		
(i) Surface type	Conical	Conical
(ii) Inclination Above horizontal	15°	20° (Recommended: 30°)
(iii) Origin	Back azimuth antenna	Back Azimuth antenna
(iv) Maximum height	15,000 meters (5,000')	600 meters (2,000')

RCL=Runway Center Line

ERCL=Extended Runway Center Line

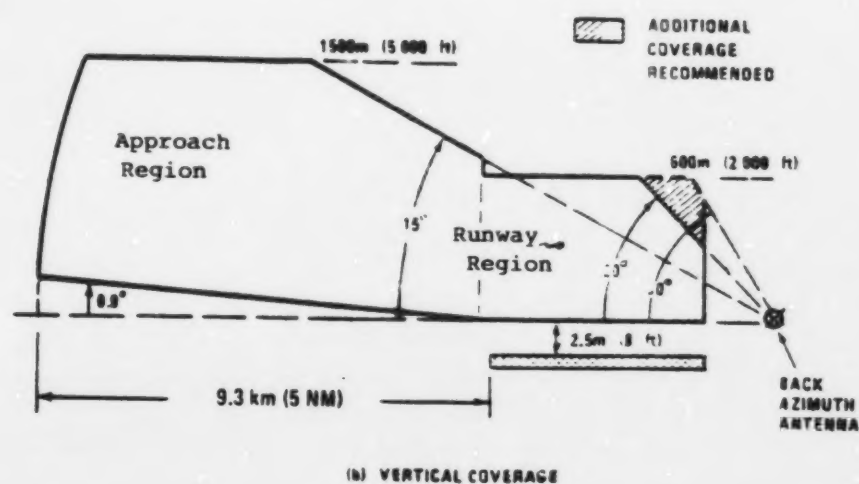
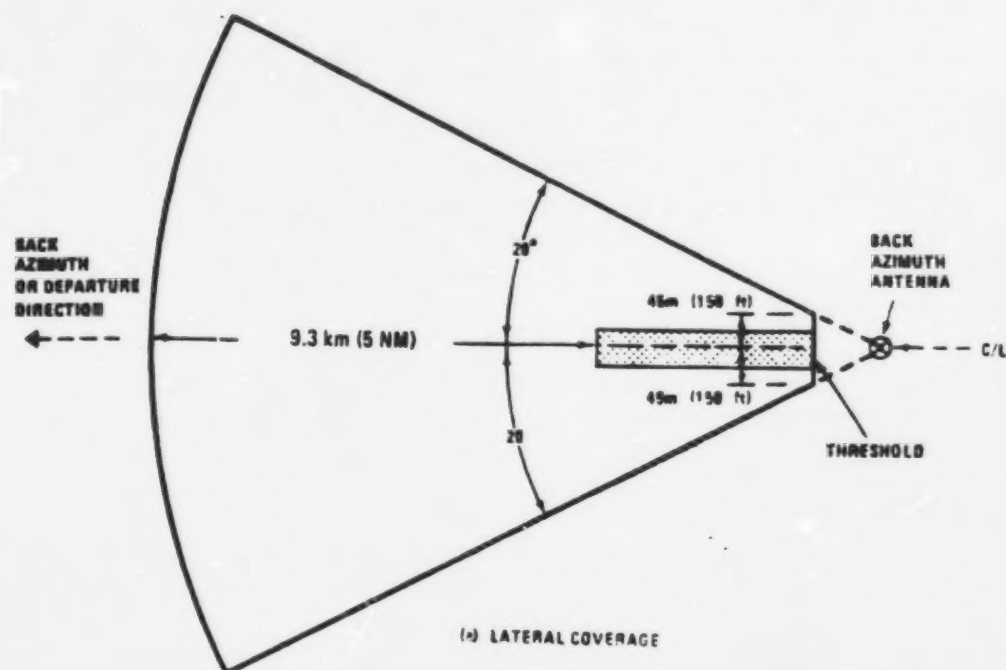


Figure 3.2 Back Azimuth Coverage

Table 3-3 Elevation Coverage (Proportional) [ICAO para. 3.11.5.3.2]

	Approach Region	Runway Region
Horizontal Limits		
(i) Lateral boundaries or sector angle	Sector equal to proportional coverage of approach AZ	N/A
(ii) Near approach boundary or sector origin	Sector origin: MLS datum point Region boundary: 75 m in front of MLS datum	N/A
(iii) Far approach boundary	37 km (20 NM) from threshold	N/A
Vertical Limits		
a) Lower limit		
(i) Surface type	- Minimum height of coverage is 2.5 m - conical surface	N/A
(ii) Inclination Above horizontal	0.9°	N/A
(iii) Origin	MLS datum point	N/A
b) Upper limit		
(i) Surface type	Conical	
(ii) Inclination Above horizontal	7.5° (recommended > 7.5°)	N/A
(iii) Origin	MLS datum point	N/A
(iv) Maximum height	6,000 meters (20,000')	N/A

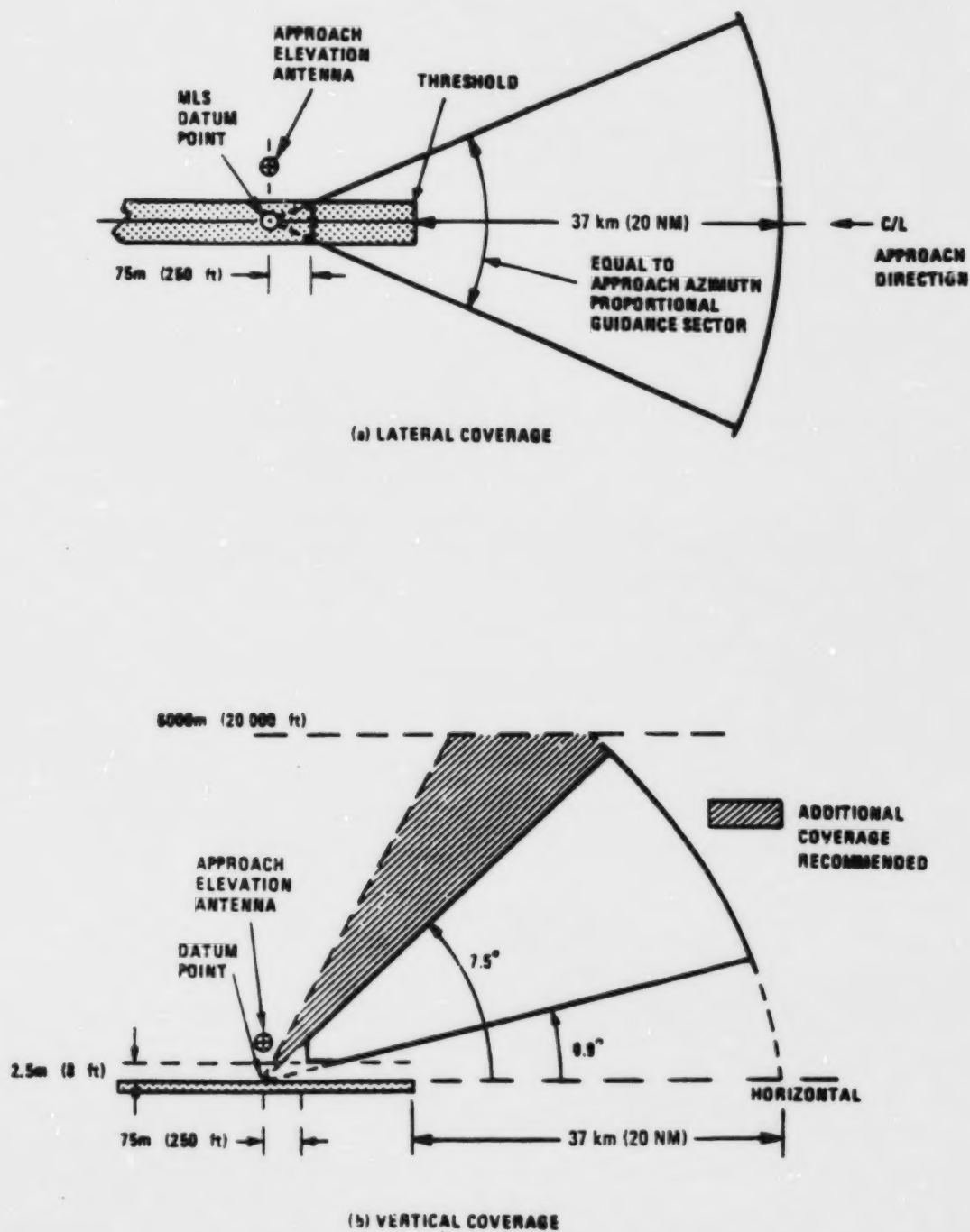


Figure 3.3 Approach Elevation Coverage

- b) Pulse pairs in angle time scan slots
 - pair 1 - adjacent to start time of TO scan
 - adjacent to stop time of FRO scan
 - implies fly left
 - pair 2 - adjacent to stop time of TO scan
 - adjacent to start time of FRO scan
 - implies fly right

(see Figure 3-4)
- (iii) Proportional coverage is established one BW inside scan start/stop boundary. (Guidance material) [ICAO ATTACH I, para. 2.3.4.1]
- (iv) When clearance is used with a narrow BW (i.e., 1°), the scanning beam should radiate for 15 μ s dwell time at start/stop angles. (Guidance material) [ICAO ATTACH I, para. 2.3.4.2]
- (v) Transmission of OCI pulses from antenna with overlapping coverage patterns should be separated by at least 10 μ s. [ICAO para. 3.11.4.6.2.3.1]
- (vi) The characteristics of the scanning functions are tabulated in Table 3.5 and illustrated in Figures 3-5 and 3-6.

3.2.5 TIME-DOMAIN-MULTIPLEX REQUIREMENTS

The function and timing requirements as specified by ICAO are as follows:

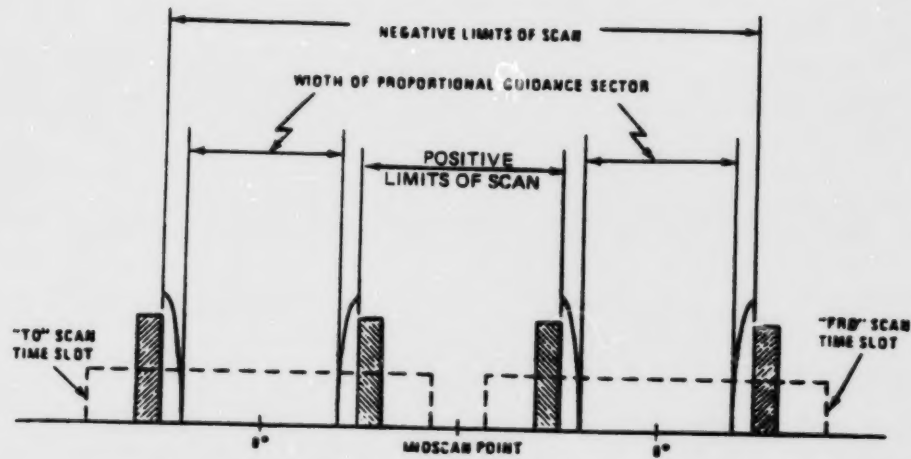
- a) Angle and data information shall be transmitted by TDM on a single carrier. [ICAO para. 3.11.4.3.1]
- b) Event timing will be synchronized to provide freedom from synchronous interference. [ICAO para. 3.11.4.3.2]
- c) The angle and data information is transmitted in the form of various functions, with the following durations and function rates (see Table 3.6, Figures 3.9 and 3.10).
- d) The functions listed in Table 4.1 are composed of the events listed in Tables 3.9 to 3.12.

Table 3.4 Signal Specifications

	DPSK ICAO para. 3.11.4.4.3.1	OCI ICAO para. 3.11.4.6.2.3 and 3.11.4.7.2	CLEARANCE ICAO para. 3.11.4.6.2.5
SIGNAL DESCRIPTION	"0"=0° phase shift "1"=180° phase shift	a) one single pulse or b) two pulses	- pulse pairs - information in power level relative to scan beam
DURATION	64 μ S	a) 100 μ S at half amplitude b) 2 pulses 50 μ S	50 μ S + 5 μ S
RISE & FALL TIMES	transition < 10 μ S - no amplitude modulation during transition - must be monotonic	< 10 μ S	< 10 μ S < 10 μ S switching time to scanning beam
AVERAGE FREQUENCY	modulation rate = 15625 Hz	one per function slot (HAZ, EL & BAZ)	one per function slot (BAZ & HAZ)
POWER LEVELS	AZ > -89.5 dBW/m ² HAZ > -89.5 dBW/m ² BAZ > -81.0 dBW/m ² EL > -89.5 dBW/m ² throughout coverage volume [ICAO para. 3.11.4.10.1]	- greater than any guidance signal in OCI sector - 5 db < clearance pulse in clearance sector - 5 db < scanning beam level in proportional level	- at least 5 db > other signals in clearance sector - at least 5 db > scanning beam in proportional coverage - > 88 dBW/m ² for AZ - > 88 dBW/m ² for HAZ - > 79.5 dBW/m ² for EL
EVENT TIME SLOT DURATION	64 μ S	128 μ S	-
STATIC PHASE JITTER	$\pm 10^\circ$	-	-

Table 3.5 Scanning Function Specifications

	HIGH RATE AZIMUTH	BACK AZIMUTH	ELEVATION
ORIENTATION OF SCAN: TO FRO	[ICAO para. 3.11.4.6.1] Clockwise Counterclockwise	[ICAO para. 3.11.4.6.1] Clockwise Counterclockwise	[ICAO para. 3.11.4.7.1] Up Down
ANGLE CONVENTION	[ICAO para. 3.11.4.6.1] + ve in direction of TO scan	[ICAO para. 3.11.4.6.1] - ve in direction of TO scan	[ICAO para. 3.11.4.7.1] + ve in direction of TO scan
BEAMSHAPE (See Figure 3.4)	[ICAO para. 3.11.5.2.1] - fan shaped - narrow in hori- zontal plane - broad in verti- cal plane	[ICAO para. 3.11.5.2.1] Same as HAZ	[ICAO para. 3.11.5.3.1] - fan shaped - - narrow in verti- cal plane - broad in hori- zontal plane
BEAMWIDTH (on boresight)	[ICAO para. 3.11.5.2.1.2] < 4° detected beam < 5° (250μS)	[ICAO para. 3.11.5.2.1.2] Same as HAZ	[ICAO para. 3.11.5.3.1.2] < 2.5°
-10 dB POINT (multipath free)	> 0.7 BW, > 0.9 BW	Same as HAZ	> 0.7 BW, < 0.9 BW
POWER DENSITY BW 1° (See Figure 3.5) 2° 3° @ approach ref. datum @ 2.5 m above runway or MLS datum point or at farthest point of runway centerline in line of sight [ICAO para. 3.11.4.10.1]	> -88.0 dBW/m ² > -88.0 dBW/m ² > -86.8 dBW/m ² 15 dB > than above 5 dB > than above 9 dB > than above for 1° BW for > 2° BW	> -79.5 dBW/m ² > -77.0 dBW/m ² > -73.5 dBW/m ² Same as HAZ	-88.0 dBW/m ² -88.0 dBW/m ² - Same as HAZ



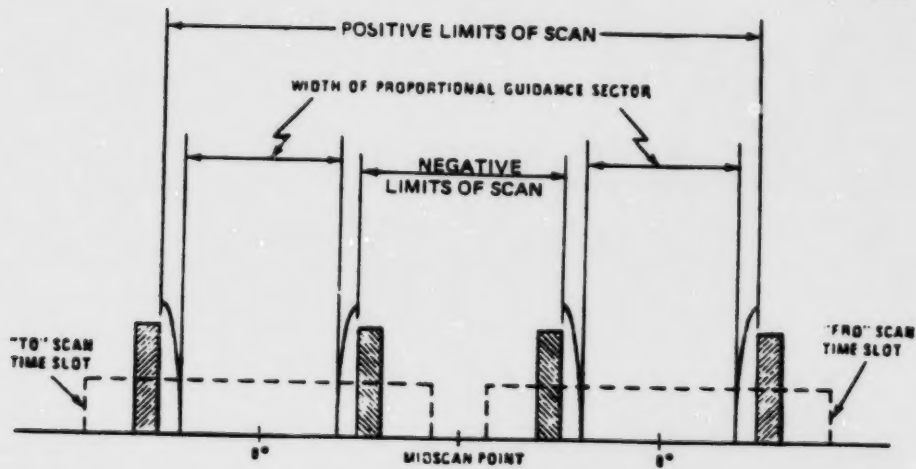
(a) APPROACH AZIMUTH

LEGEND

FLY LEFT
CLEARANCE
PULSES

FLY RIGHT
CLEARANCE
PULSES

SCANNING BEAR
PULSES



(b) BACK AZIMUTH

Figure 3.4 Clearance Pulse Conventions for Azimuth Functions

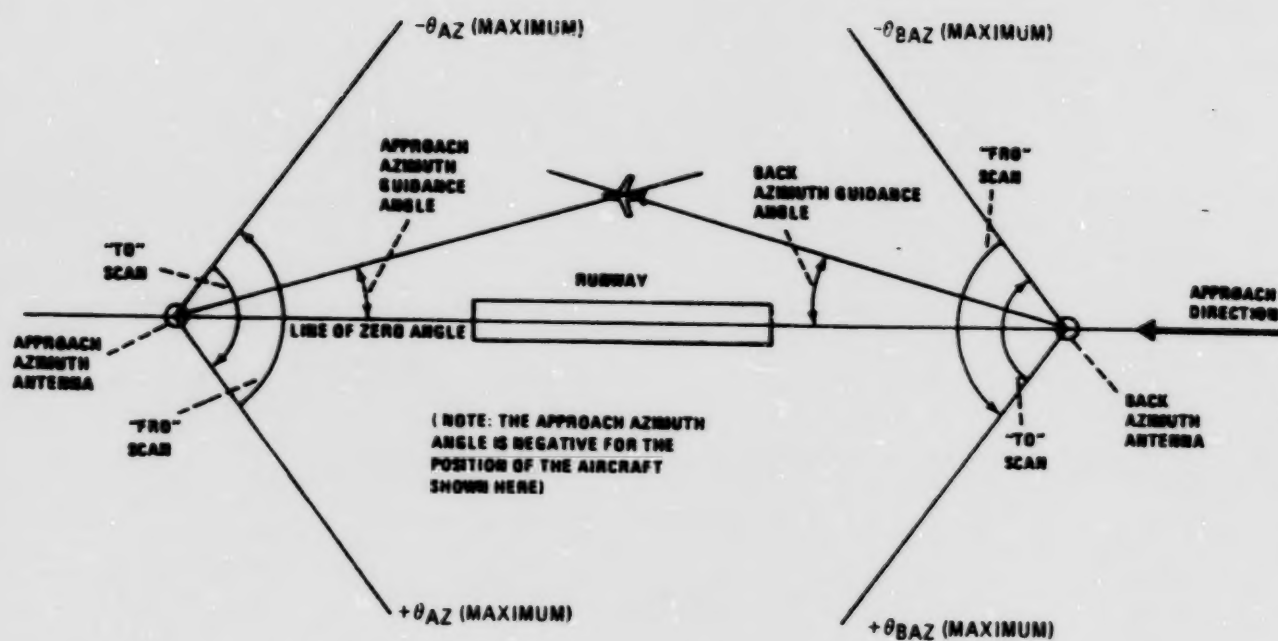


Figure 3.5 Scanning Conventions for Azimuth Guidance Functions

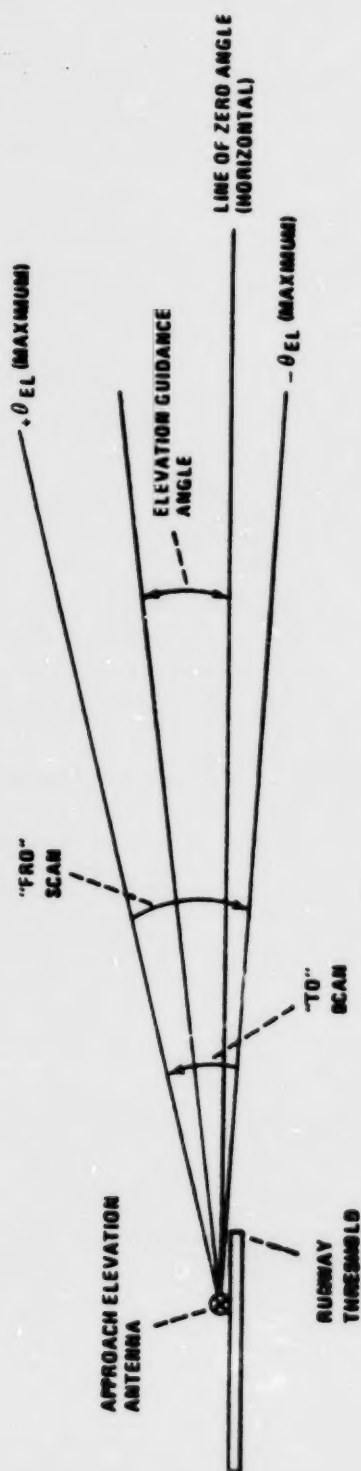
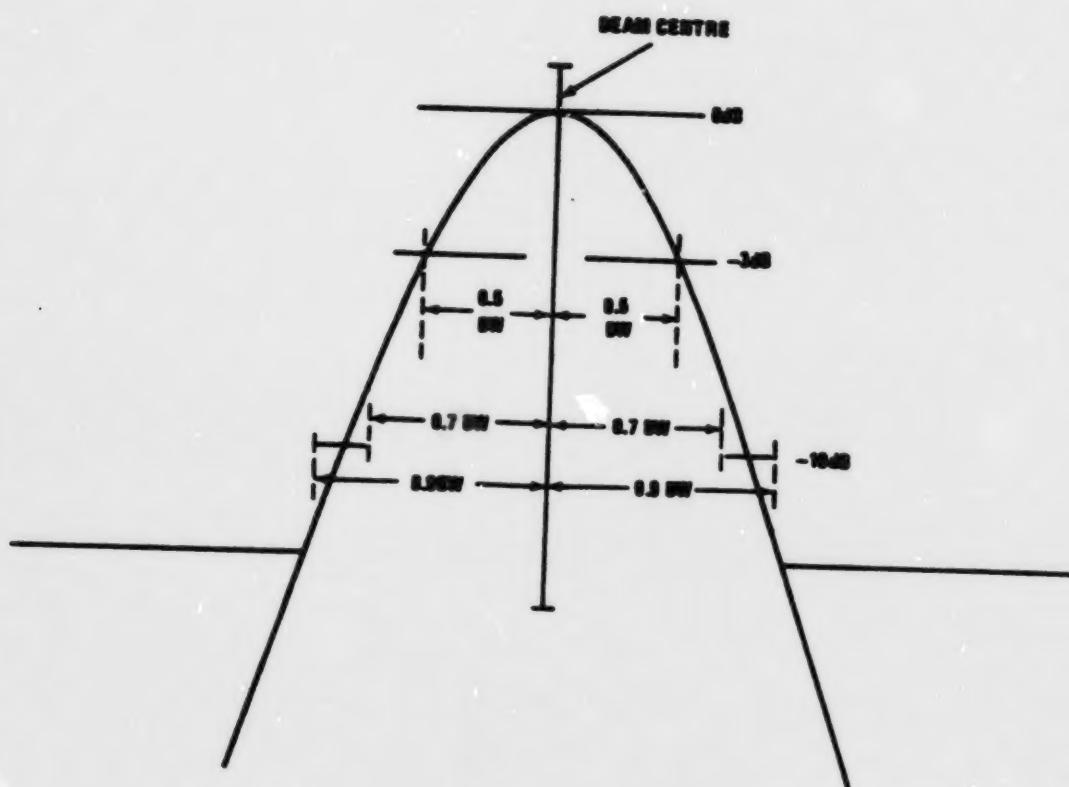


Figure 3.6 Scanning Conventions for Approach Elevation and Flare Guidance Functions



NOTES:

THE BEAM ENVELOPE IS SMOOTHED BY A 28 kHz VIDEO FILTER BEFORE MEASUREMENT.

BW = BEAMWIDTH.

Figure 3.7 Far Field Dynamic Signal-in-Space

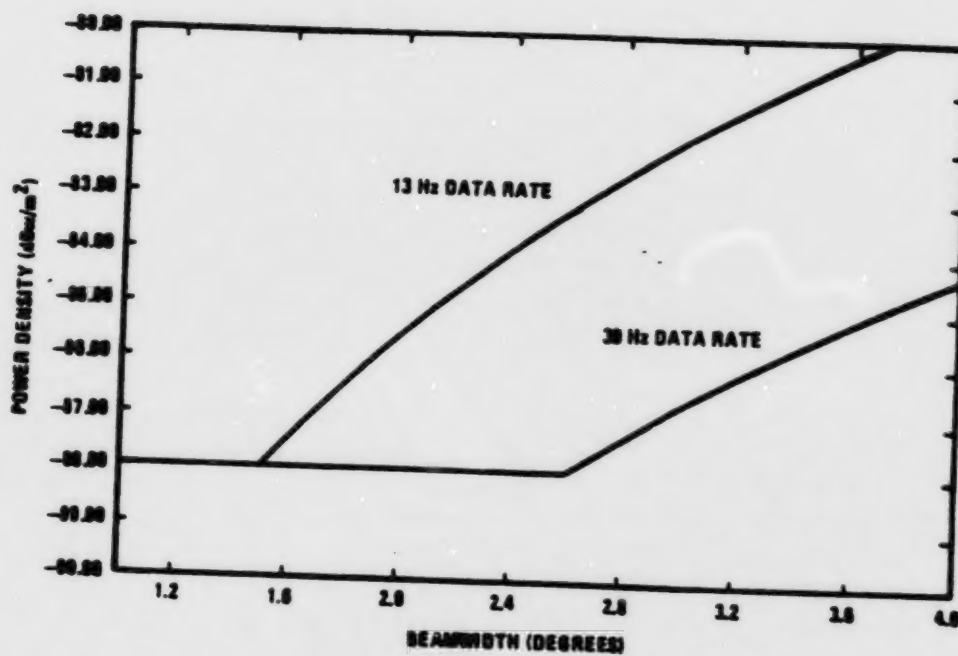


Figure 3.8 Power Density Requirements for Various Antenna Beamwidths

3.2.5.1 Event Timing

- a) Preamble: (Table 3.13) [ICAO para. 3.11.4.4.1]
 Consists of:
 (i) Carrier Acquisition
 (ii) Receiver reference time code (5 bits)
 - time of last phase transition midpoint shall be receiver
 reference time
 (iii) Function Identification Code (5 bits) (see Table 3.14)
- b) Morse Code (AZ and HAZ functions only [ICAO para. 3.11.4.6.2.1])
 - 4 letter ground identifier starting with letter M
 - coded in international Morse Code
 - frequency of code: at least 6/minute
 - "1" initiates symbol
 - "0" terminates symbol

Table 3.6 Function Rates
 [ICAO para. 3.11.4.3.3 and para. 3.11.4.3.4]

Function	Time Duration (mS)	Average Frequency (Hz)	Maximum Time Interval Between Transmissions (sec)	
			ICAO	AWOP-10
High Rate Azimuth	11.9	39 ± 1.5	-	-
Back Azimuth	11.9	6.5 ± 0.25	-	-
Elevation	5.6	39 ± 1.5	-	-
Data Word #1	3.1	-	0.4	1.0
Data Word #2	3.1	-	0.16	0.16
Data Word #3	3.1	-	10	1.0
Data Word #4	3.1	-	10	1.0
Data Word #5	3.1	-	10	1.0
Data Word #6	3.1	-	10	1.0
Data Word #7	3.1	-	1.0	-
Data Word #8	3.1	-	10	-
Auxiliary data	5.9	-	-	-
Auxiliary data word A1, A2, A3, A4	5.9	-	-	1.0

Table 3.7 Morse Code Timing

Event	Time Duration (sec.)	Number of HAZ Functions
Dot	0.13 - 0.16	6-7
Dash	0.39 - 0.48	18-22
Interval between symbols	$(0.13 - 0.16) \pm 10\%$	6-8
Interval between characters	> 3 "dots"	18-22

- c) Airborne Antenna Selection [ICAO para. 3.11.4.6.2.2]
- "zero" DPSK signal
 - 6 bits long
 - available throughout coverage sector

3.2.5.2 Sequence Timing [ICAO para. 3.11.4.3.5]

- (i) The sequence timing must be varied in a manner such that repetitive transmissions of any one function are protected from synchronous interference.
- (ii) Function transmissions can occur in any order, except that data word #2 must precede the BAZ function
- (iii) The sequences of Figure 3.11 have been demonstrated to provide protection from synchronous interference.

3.2.5.3 Cycle Timing [Attachment I, para. 2.1.4]

The recommended cycle timing that provides freedom from synchronous interference is illustrated in Figure 3.11. Its requirements are:

- (i) Duration of SEQUENCE #1 plus SEQUENCE #2 $\leq$ 134 m sec.
- (ii) Data words can be transmitted in open time periods as specified.
- (iii) Maximum full cycle length is 615 m sec.
- (iv) Available number of data and auxiliary word slots in a full cycle are:
 - a) SEQUENCE #1 x 4 x 4 data words = 16
 - b) SEQUENCE #2 x 4 x data word #2 = 4
 - c) spacing between sequences = 12
 - TOTAL # word slots = 32

3.2.5.4 TDM Hierarchy

EVENT $\longrightarrow$ FUNCTION $\longrightarrow$ SEQUENCE $\longrightarrow$ CYCLE

- a) Sequences:
 - (i) SEQUENCE #1
 - (ii) SEQUENCE #2
- b) Functions:
 - ANGLE:
 - (i) High Rate Azimuth
 - (ii) Back Azimuth
 - (iii) Elevation
 - DATA:
 - (i) Basic data
 - (ii) Auxiliary data

c) Events:

Table 3.8

Event	Signal Type
(i) Preamble: - carrier acquisition - reference time code - function ID code	RF carrier DPSK DPSK
(ii) Sector signals: - ground equipment ID (Morse Code) - Airborne Antenna selection - OCI pulses - Test pulse	DPSK DPSK Pulse Pulse
(iii) TO SCAN	Scanning beam
(iv) FRO SCAN	Scanning beam
(v) CLEARANCE	Pulse

FUNCTION TIMING

Table 3.9 Approach Elevation Function Timing
[Appendix A Table A-4]

Event	Event Time Slot Begins at:		Time Slot Duration (μ Sec)
	15.625 kHz Clock Pulse (Number)	Time (milli-seconds)	
PREAMBLE	0	0	1600
PROCESSOR PAUSE	25	1.600	128
OCI	27	1.728	128
TO SCAN*	29	1.856	1550
PAUSE		3.406	400
MIDSCAN POINT		3.606	-
FRO SCAN*		3.806	1550
END FUNCTION (AIRBORNE)		5.356	244
END GUARD TIME; END FUNCTION (GROUND)		5.600	

Table 3.10 High Rate Approach Azimuth and
Back Azimuth Function Timing
[Appendix A Table A-3]

Event	Event Time Slot Begins at:		Time Slot Duration (μ Sec)
	15.625 kHz Clock Pulse (Number)	Time (milli-seconds)	
PREAMBLE	0	0	1600
MORSE CODE	25	1.600	64
ANTENNA SELECT	26	1.664	384
REAR OCI	32	2.048	128
LEFT OCI	34	2.176	128
RIGHT OCI	36	2.304	128
TO TEST	38	2.432	128
TO SCAN*	40	2.560	4200
PAUSE		6.760	600
MIDSCAN POINT		7.060	-
FRO SCAN*		7.360	4200
FRO TEST PULSE		11.560	128
END FUNCTION (AIRBORNE)		11.688	212
END GUARD TIME; END FUNCTION (GROUND)		11.900	

Table 3.11 Basic Data Function Timing
[Appendix A Table A-6]

Event	Event Time Slot Begins at:		Time Slot Duration (μ Sec)
	15.625 kHz Clock Pulse (Number)	Time (milli-seconds)	
PREAMBLE	0	0	1600
DATA TRANSMISSION: (BITS $I_{1,1} - I_{1,0}$)	25	1.600	1152
PARITY TRANSMISSION: (BITS $I_{1,1} - I_{1,2}$)	43	2.752	128
END FUNCTION (AIRBORNE)	45	2.880	220
END GUARD TIME; END FUNCTION (GROUND)		3.100	

Table 3.12 Auxiliary Data Function Timing
[Appendix A Table A-8]

Event	Event Time Slot Begins at:		Time Slot Duration (μ Sec)
	15.625 kHz Clock Pulse (Number)	Time (milli-seconds)	
PREAMBLE	0	0	1600
ADDRESS TRANSMISSION: (BITS $I_{1,1} - I_{2,0}$)	25	1.600	512
DATA TRANSMISSION: (BITS $I_{2,1} - I_{2,2}$)	33	2.112	3328
PARITY TRANSMISSION: (BITS $I_{7,1} - I_{7,2}$)	85	5.440	256
END FUNCTION (AIRBORNE)	89	5.696	204
END GUARD TIME; END FUNCTION (GROUND)		5.900	

Table 3.13 Preamble Timing

[Appendix A Table A-1]

Event	Event Time Slot Begins at:		Time Slot Duration (μ Sec)
	15.625 kHz Clock Pulse (Number)	Time (milli- seconds)	
CARRIER ACQUISITION: (CW TRANSMISSION)	0	0	832
RECEIVER REFERENCE TIME CODE:			
$I_1 = 1$	13	0.832	320
$I_2 = 1$	14	0.896	
$I_3 = 1$	15	0.960	
$I_4 = 0$	16	1.024	
$I_5 = 1$	17	1.088**	
FUNCTION IDENTIFICATION:			
I_6	18	1.152	448
I_7	19	1.216	
I_8	20	1.280	
I_9	21	1.344	
I_{10}	22	1.408	
I_{11}	23	1.472	
I_{12}] PARITY BITS	24	1.536	
END PREAMBLE	25	1.600	

* Applies to all functions transmitted.

** Reference time for receiver synchronization for all function timing.

Table 3.14 Function Code
[ICAO para. 3.11.4.4.3.3]

Function (AWOP-10)	Function (ICAO)	I ₆	I ₇	I ₈	I ₉	I ₁₀	I ₁₁	I ₁₂
	APPROACH AZIMUTH HIGH RATE	0	0	1	1	0	0	1
	APPROACH AZIMUTH	0	0	1	0	1	0	0
	APPROACH ELEVATION	1	1	0	0	0	0	1
	FLARE ELEVATION	0	1	1	0	0	0	1
	BACK AZIMUTH	1	0	0	1	0	0	1
	360°AZIMUTH	0	1	0	0	1	0	1
	BASIC DATA 1	0	1	0	1	0	0	0
	BASIC DATA 2	0	1	1	1	1	0	0
	BASIC DATA 3	1	0	1	0	0	0	0
	BASIC DATA 4	1	0	0	0	1	0	0
	BASIC DATA 5	1	1	0	1	1	0	0
	BASIC DATA 6	0	0	0	1	1	0	1
AUXILIARY DATA A	BASIC DATA 7	1	1	1	0	0	1	0
AUXILIARY DATA B	BASIC DATA 8	1	0	1	0	1	1	1
AUXILIARY DATA C	AUXILIARY DATA	1	1	1	1	0	0	0

NOTE 1 - The function identification codes have been chosen so that parity bits I₁₁ and I₁₂ obey the equations:

$$I_6 + I_7 + I_8 + I_9 + I_{10} + I_{11} = \text{EVEN}$$

$$I_6 + I_8 + I_{10} + I_{12} = \text{EVEN}$$

3.2.5.5 Angle Guidance Parameters [ICAO para. 3.11.4.5]

Angle guidance information is encoded by the amount of time separation between center beams of TO and FRO pulses.

The coding is interpreted according to:

$$\phi = (T_O - t) V/2$$

3.2.5.6 TDM Timing Requirements [ICAO para. 3.11.4.3.4]

(i) events accurate to within $\pm 2 \mu S$

NOTE: This specification applies to all timing events; the one exception being noted in paragraph (iii) below.

(ii) timing jitter $< \pm 1 \mu S$ RMS

(iii) To and FRO scans to be symmetrical about mid scan point T_m and the difference between the mid scan time and the receiver reference time is to be accurate to within $10 \mu s$.

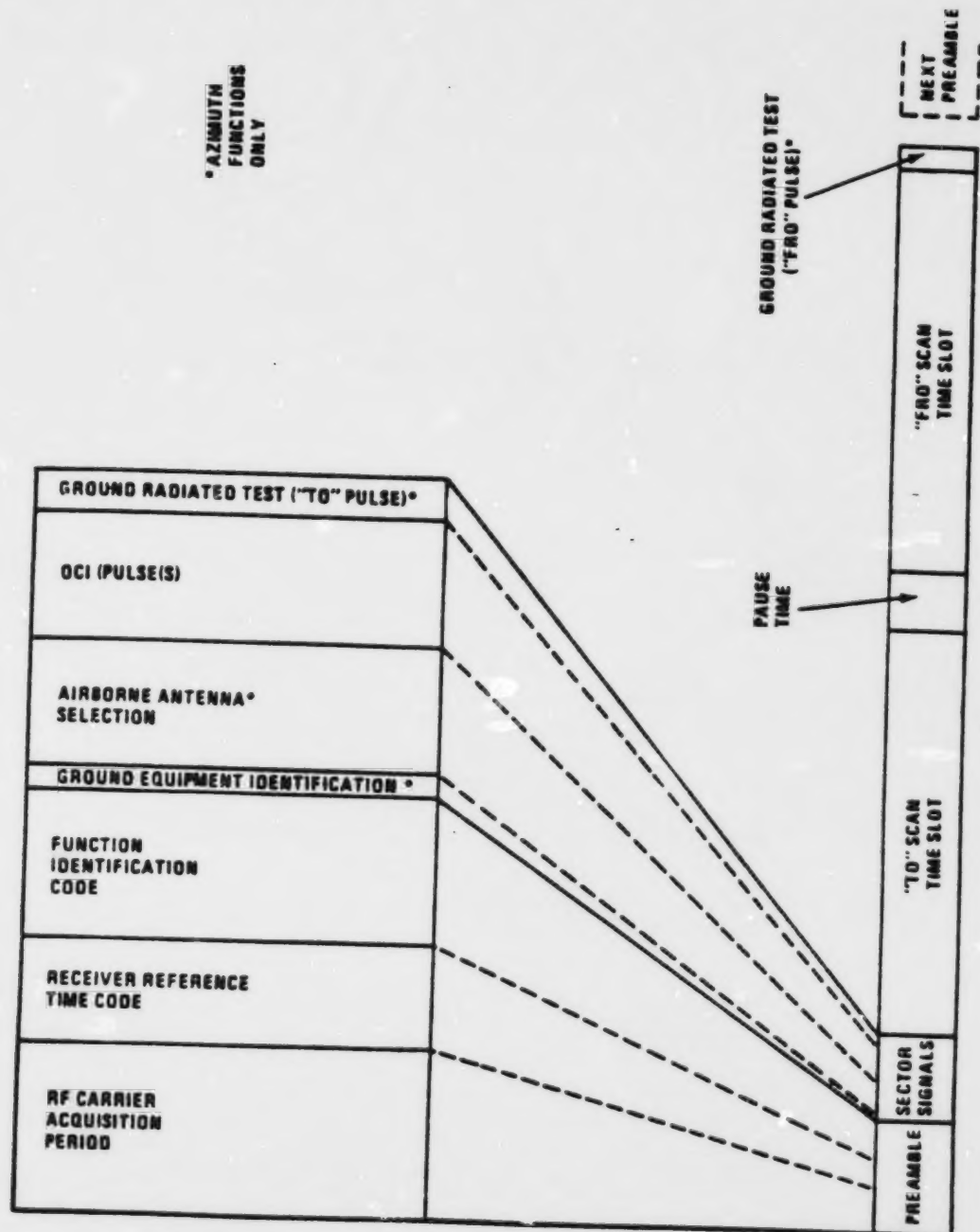


Figure 3.9 Angle Function Organization

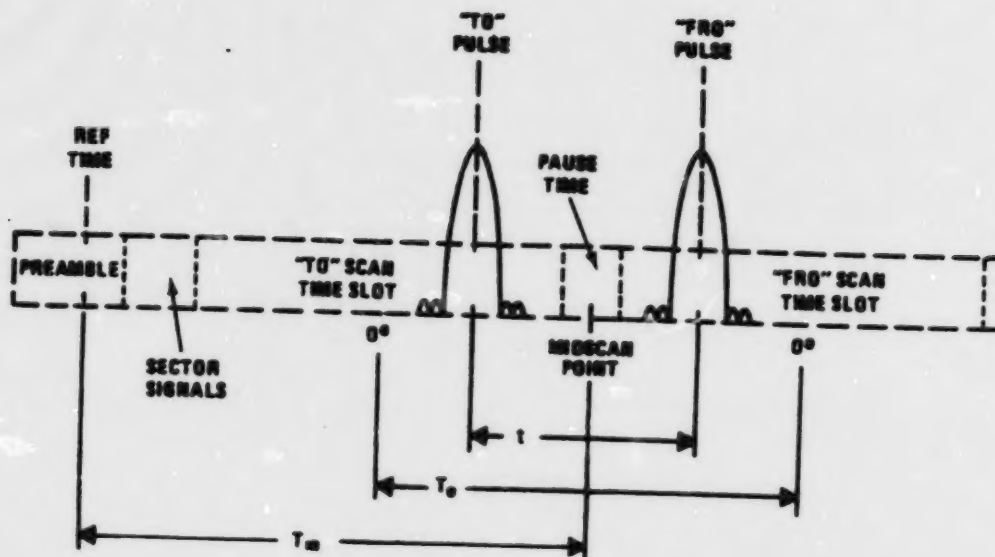


Figure 3.10 Angle Scan Timing Parameters

SEQUENCE #1	TIME (ms)	SEQUENCE #2
APPROACH ELEVATION	0	APPROACH ELEVATION
HIGH RATE APPROACH AZIMUTH	10	HIGH RATE APPROACH AZIMUTH
4 BASIC DATA WORDS (NOTE 1)	20	(NOTE 2)
HIGH RATE APPROACH AZIMUTH	30	BACK AZIMUTH
APPROACH ELEVATION	40	HIGH RATE APPROACH AZIMUTH
HIGH RATE APPROACH AZIMUTH	50	APPROACH ELEVATION
APPROACH ELEVATION	60	HIGH RATE APPROACH AZIMUTH
	64.9	APPROACH ELEVATION
	67.5	
	(NOTE 3)	

NOTES:

1. BASIC DATA WORDS MAY BE TRANSMITTED IN ANY OPEN TIME PERIODS.
2. WHEN BACK AZIMUTH IS PROVIDED, BASIC DATA WORD #2 MUST BE TRANSMITTED ONLY IN THIS POSITION.
3. THE TOTAL TIME DURATION OF SEQUENCE #1 PLUS SEQUENCE #2 MUST NOT EXCEED 134 ms.

—Transmission sequence pair which provides for the MLS high rate approach azimuth angle guidance function

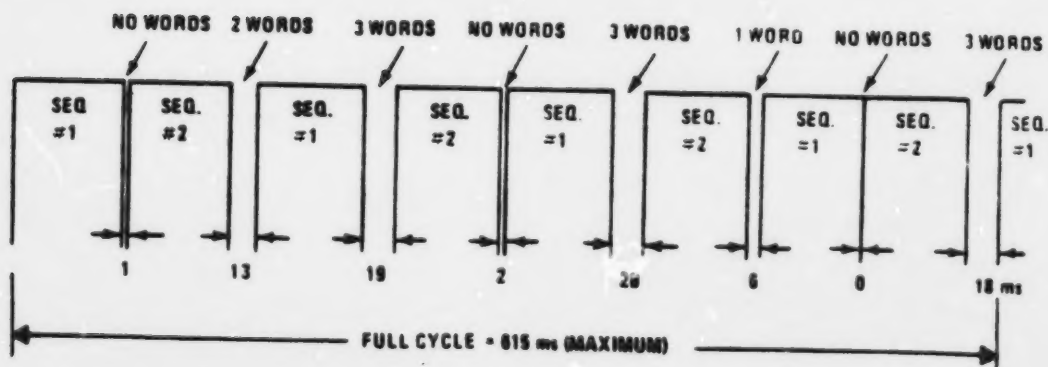


Figure 3.11 Complete Multiplex Transmission Cycle Showing Open Time Periods Available For Data Words

3.2.6 SYSTEM ACCURACIES

The required system accuracies at the reference datum are listed in Table 3.15. Tables 3.16, 3.17 and 3.18 tabulate the degradation in system accuracy over the region of coverage for the approach azimuth, back azimuth and elevation functions respectively. Table 3.19 tabulates the required ground equipment accuracy. Accuracies are computed from linear requirements (in which the error is expressed as a distance), and converted to an angle for specific runway lengths or minimum glide paths. See Appendix A for equations used for the conversion from linear to angular units.

3.2.7 MONITOR AND CONTROL REQUIREMENTS [ICAO para. 3.11.5.2.3 and para. 3.11.5.3.3]

- a) High rate Azimuth, Back Azimuth and Elevation monitor systems will cause the respective function to stop radiating and a warning issued if any of the following conditions persist for more than 1 second:
 - (i) PFE limits exceeded
 - (ii) radiated power specification violated
 - (iii) error in preamble more than once in a second
 - (iv) error in TDM synchronization
 - b) Failure of the monitor shall cause radiation to cease.
 - c) Fault clearance and switching to standby shall be achieved within 1 second.
 - d) If fault clearance or switching to standby is not achieved in 1 second, the system will be shut down for at least 20 seconds.
 - e) An error in a data word will cause radiation of that word to cease, if it persists.
- NOTE: It is recommended that the term "persists" be interpreted as a data word being in error in two successive transmissions.
- f) Table 3.20 illustrates the effects of a particular function failure on the other MLS functions.

Table 3.15 System Guidance Accuracies at Reference Datum ($\pm$ Degrees)
 [ICAO para. 3.11.4.9, 3.11.4.9.5 and 3.11.4.9.6]

		PFE	PFN	CMN	Recommended PFE
Approach AZ					
Distance from approach ref. datum to AZ antenna (m)	500	0.69	0.40	0.1	0.46
	1500	0.23	0.13	0.1	0.15
	3000	0.12	0.069	0.061	0.076
	4267	0.081	0.047	0.043	0.050
BAZ					
Distance from BAZ antenna to BAZ ref. datum (m)	900	0.43	0.25	0.1	
	1500	0.23	0.13	0.1	
	2000	0.17	0.10	0.09	
Elevation					
Assume a minimum glide path of 3° (i.e., 287 m to ref. datum)		0.12	0.079	0.059	

Table 3.16 Azimuth Accuracy ($\pm$ Degrees) Limits
 [ICAO para. 3.11.4.9.4.2 and 3.11.4.9.4.3]

		PFE	PFN	CMN	PFE (Recommended)
Approach Ref. Datum		0.115	0.066	0.06	0.077
Elevation: $\theta < 9^\circ$	Distance: @ 37 km ERC: 0.23	@ 37 km ERC: 0.132	@ 18.5 km ERC: 0.078	@ 37 km ERC 0.154	
	AZ Angle: $\phi = \pm 40^\circ$	0.345	0.198	0.101	0.23
Elevation: $\theta = 15^\circ$	AZ Angle: $\phi = 0^\circ$	0.46	0.264	0.078	0.308
	$\phi = \pm 40^\circ$	0.69	0.396	0.101	0.46

NOTE: For AZ Antenna 3048 m (10000') From Threshold

ERC= Extended Runway Centerline

ϕ = Azimuth Angle

Θ = Elevation Angle

Table 3.17 System Back Azimuth Accuracy Limits ($\pm$ Degrees)
 [ICAO para. 3.11.4.9.5.1]

		PFE	PFN	CMN
BAZ Ref. Datum		0.229	0.132	0.12
Elevation: $\theta < 9^\circ$	Distance: @ 9.27 km ERC:	0.458	0.264	0.156
	AZ Angle: $\phi = \pm 20^\circ$	0.687	0.396	0.203
Elevation: $\theta = 15^\circ$	AZ Angle: $\phi = 0^\circ$	0.916	0.528	0.156
	$\phi = \pm 20^\circ$	1.374	0.792	0.203

NOTE: For BAZ Antenna 5000' (1524 m) From Ref. Datum

Table 3.18 System Elevation Accuracy Limits ($\pm$ Degrees)
 [ICAO para. 3.11.4.9.6.1 to 3.11.4.9.6.3]

		PFE	PFN	CMN	Recommended PFE	Recommended CMN
Approach Ref. Datum		0.12	0.079	0.059		
Elevation: On minimum glide path	Distance: @ 37 km ERC: 0.2	@ 37 km ERC: 0.2	@ 37 km ERC: 0.2	@ 18.5 km ERC: 0.077		
	Angle: $\phi = \pm 40^\circ$	0.26	0.26	0.1		
Elevation: $\theta = 15^\circ$	Angle: $\phi = 0^\circ$	0.24	0.16	0.12*		
	$\phi = \pm 40^\circ$	0.31	0.31	0.13		
Elevation: $\theta < 60^\circ$ of minimum Glide Path	Angle: $\phi = 0^\circ$	0.72	0.47	0.35	0.35	0.17
	$\phi = \pm 40^\circ$	0.8	0.94	0.4	0.35	0.2

* Except that directly above reference datum CMN $< 0.07^\circ$

NOTE: Minimum Glide Path = 3°

ERC= Extended Runway Centerline

ϕ = Azimuth Angle

θ = Elevation Angle

Table 3.19 Ground Equipment Accuracy Limits ($\pm$ Degrees)
 [ICAO para. 3.11.5.2.4 and para. 3.11.5.2.5]

	PFE (Mean)	CMN (Recommended)
AZIMUTH GUIDANCE (i) Typical Max: (3353 m, 11000') from AZ antenna to approach reference datum	0.051	0.017 (Absolute Limit of 0.03 See Note 1)
(ii) Worse Case: 4268 m, (14000')	0.04	0.013 (Absolute Limit of 0.03) See Note 1)
ELEVATION GUIDANCE (i) MGP = 3° 287 m, (942') to reference datum	0.06	0.03
(ii) MGP = 2.5° 344 m, (1123') to reference datum	0.05	0.025

MGP = minimum glide path

Note 1: The accuracy limits are defined in terms of absolute distance. For runway lengths less than 1910 m (6265'), the absolute angular distance would supercede the distance limit.

Table 3.20 Interrelationship of Ground Equipment Monitor and Control Action
[Attachment I, Section 6]

Sub-System Failure	Resultant Action						
	Approach Azimuth	Approach Elevation	Flare	Back Azimuth	Basic Data Word	DME or DME/P	Auxiliary Data
Approach azimuth	*	*	*				
Approach elevation		*					
Flare			*				
Back azimuth				*			
Basic data word					*		
DME or DME/P						*	
Auxiliary data							*

* Indicates radiation should cease.

3.3 ENVIRONMENTAL PERFORMANCE

The MLS system must meet all the performance requirements stated in Sections 3.1 and 3.2 over the full range of environmental conditions which might be expected at Canadian airports. These conditions are specified in Table 3.21. (Reference: Transport Canada, DTA 1000, General Specification for Procurement of Electronic Equipment, Jan. 1981.)

Table 3.21

(1) Ambient Temperature	
(operating)	-55°C to 55°C
(non-operating)	-55°C to 65°C
Induced Temperature Rise	
(solar radiation)	Min. exposure of 4 hrs. at 1135 W/m ² /h.
(2) Adverse Weather	
(operating)	Up to 100% humidity, wind 158 km/h. with driving rain or 4 cm. of ice loading
(non-operating)	Wind 240 km/h. with 4 cm. of ice loading
(3) Salt Atmosphere	As encountered in coastal areas
(4) Duty Cycle	Continuous unattended mode except for scheduled maintenance interruptions
(5) Sand and Dust	Fine dust, up to 150 microns
(6) Altitude (operating)	Sea Level to 3,000 m.

In addition to the conditions defined in Table-3.21, performance to specification is required when the radome heater is activated during icing conditions.

3.4 COMMENTS ON THE ICAO SARPS

3.4.1 POSSIBLE AMENDEMENTS TO THE SARP

The ICAO specifications discussed previously in this section do not include the changes proposed in AWOP-10 (Ref. 2). However, these proposed changes have been noted, and in the event that they do become the accepted standard of ICAO, the changes will not impact greatly upon the implementation of the MLS test system. This is because the majority of the changes in AWOP-10 are clarifications to the wording of the specifications. The area of major modification that would impact on the test system design hardware and software is related to event timing and concerns the modifications to the contents of the data words and the format of the auxiliary data words. Unless the changes are made retroactive, two conflicting formats could exist. It would be necessary, therefore, for the MLS to transmit a unique identity code which would define which format was being transmitted. This is an equal problem for both testing and aircraft usage.

3.4.2 FUNCTION TIMING REQUIREMENTS

The requirements of the cycles, sequences and functions of Section 3.2.5, though they have been recommended by ICAO, do not constitute a requirement. As a result, a manufacturer could vary the order and timing of the function transmissions significantly and still meet the ICAO specifications.

Thus at the beginning of a commissioning test procedure, it would be desirable to perform a training run to determine the exact timing sequence or "signature" of the MLS system being installed, which could be used as a check when the system was subsequently tested, for example, during Periodic Testing. Implementation of such a procedure is feasible using either hardware or software techniques.

4.0 STUDY OF MEASUREMENT TECHNIQUES

There is a profusion of alternative techniques available to measure the parameters defined in Section 3.0. The objective of this section is to propose and discuss techniques most suitable for each task, defining the advantages and disadvantages of each.

The measurement techniques are discussed under the following major headings:

- Spatially Invariant Parameters
- Radiated Signal Parameters
- Environmental Sensitivity of MLS Antenna

4.1 SPATIALLY INVARIANT PARAMETERS

Spatially invariant parameters (SIP) refer to the parameters of the MLS which are not a function of the relative position and displacement of the observer with respect to the MLS antennas. These parameters can therefore be measured either directly from the equipment or using the signal as radiated since multipath does not effect the measurement results. Those ICAO specifications which fall into the SIP category are tabulated in Table 4.1. It should be noted that the SIPs are classified into several functional categories, namely:

- a) frequency measurements
- b) time interval measurement
- c) function decoding and triggering
- d) data processing
- e) phase measurement
- f) monitor and control

Table 4.1 SIP's

FREQUENCY MEASUREMENTS - carrier frequency - frequency tolerance of carrier - frequency stability
TIME INTERVAL MEASUREMENT - function rates and timing - sequence rates and timing - cycle rates and timing - rise and fall times (OCI, DPSK and clearance - waveform duration - timing accuracy - RMS timing jitter
FUNCTION DECODING - function identification
DATA PROCESSOR - integrity of digital data - function identification - calculation of time interval measurements - Morse Code functions
MONITOR AND CONTROL - integrity of monitor - alarm limits of monitor

4.1.1 RECEIVING SYSTEM CONFIGURATIONS

Two potential receiving system configurations that could be used as an MLS test unit are illustrated in Figures 4.1 and 4.2. Each configuration includes several other functional blocks besides those required to perform the tasks of Table 4.1. These include the antenna, amplifier, filter unit, the downconverter, the amplitude detector (diode detector or log amp), the DPSK demodulator, and the angle processor (discussed in Section 4.2.3). Each of these functional blocks converts the received signal to a form suitable for a particular measurement. Some of the functional blocks are required to measure spatially variant parameters; these are discussed in greater detail in Section 4.1.2 and Section 4.2.

The selection of a test configuration as well as its advantages, disadvantages, the technical feasibility, and the possible implementations of each functional block and their ramifications on the accuracy of the measurement being performed are discussed in the following paragraphs. Examples of measuring devices or products currently available from manufacturers are also tabulated.

4.1.1.1 Antenna Input Signal

Initially the RF signal is received by the test facility antenna and passed through a bandpass filter to remove out-of-band high level interference which could produce intermodulation products. It should be noted that a downconverter would be designed to eliminate undesired signals. If a downconverter is not used, other techniques such as filters and/or directional antennas will be required. An optional amplifier may be necessary at this point to increase the power level of the received signal to within the dynamic range of the test measurement equipment. Preliminary calculations indicate that the received signal strength will be -10 to -20 dBm at a range of 40 meters (see Appendix A), which is well within the dynamic range of most measurement equipment.

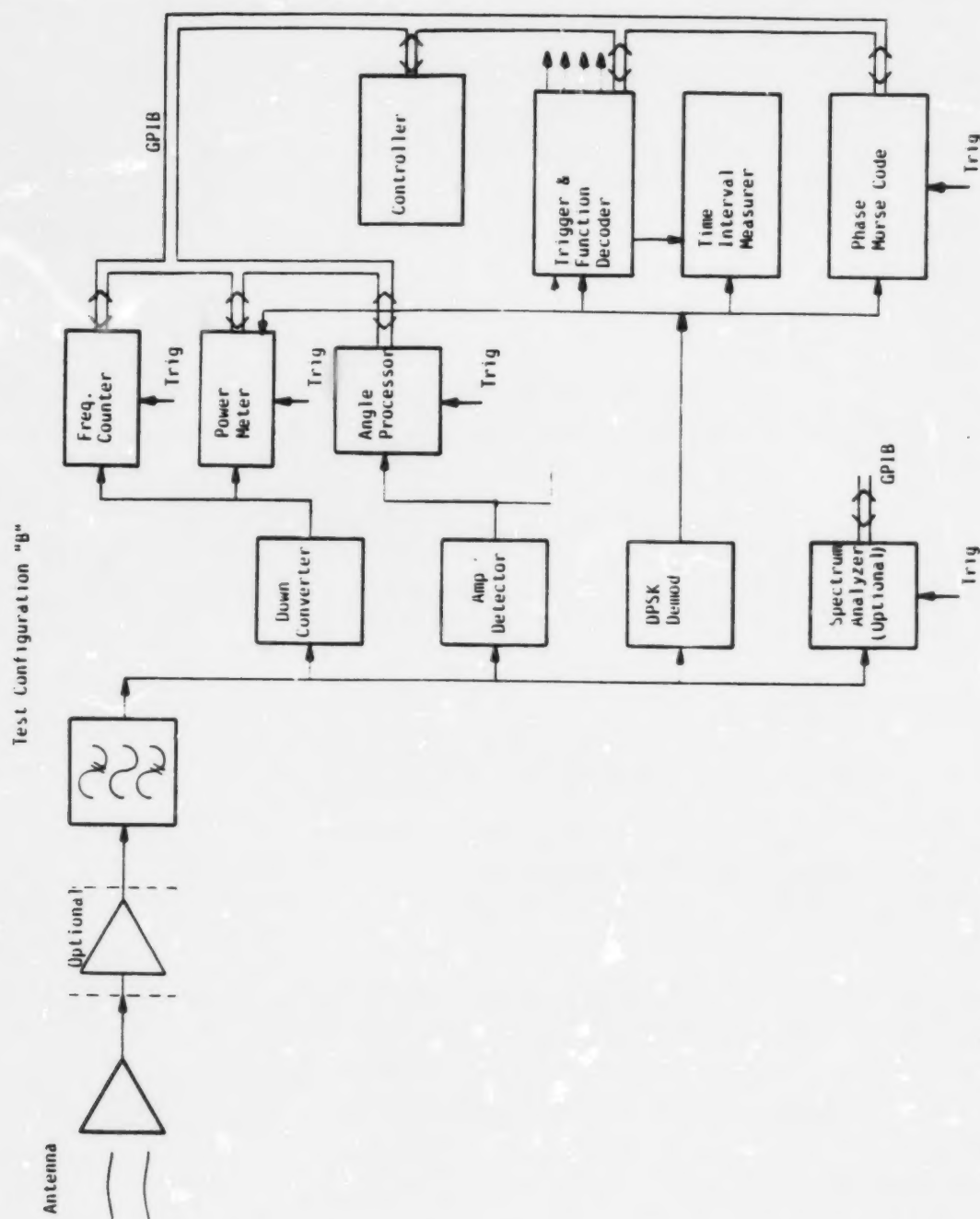


Figure 4.2 Test Configuration B

4.1.1.2 Downconverter

The downconverter is necessary in any test configurations and can be implemented in several possible ways. An MLS receiver could be utilized as a downconverter, however, the MLS receiver would have to be modified in order to provide an IF output (preferably a log IF output) as well as a DPSK output. The inherent danger of such an approach is that if the MLS receiver downconverter has accuracy limitations, then the test configuration will likewise be degraded by these accuracy limitations.

The second implementation approach involves a custom made downconverter, involving a single, dual, or triple down conversion. Based on filtering requirements and current technology, the IF frequency after a single down conversion would be approximately 160 MHz. If a second down conversion stage was employed, then the IF output frequency would likely be in the range of 10-40 MHz. It should be noted that while the operating frequency range of most measuring instruments extend up to 100 MHz, most do not operate in the 160 MHz range. Therefore, it would be desirable to have a dual downconverter system.

Other possible downconverter implementations include a microwave receiver, and the possibility of using a spectrum analyzer as a downconverter. Using a microwave receiver would involve obtaining and paying for technology that is not necessary for an MLS application (i.e., most current state of the art microwave receivers tend to be wideband receivers, whereas the MLS signal is in fact a narrowband signal). If a spectrum analyzer was employed for spectrum analysis in the test configuration, then a cost effective method of downconverting would be to use the IF output present on the back panel of most spectrum analyzers. However, the accuracy and phase noise characteristics of the IF output may not meet the stringent MLS angle accuracy requirements.

4.1.1.3 DPSK Demodulator

The DPSK demodulator also has several possible implementations. As was mentioned previously, an MLS receiver could be employed to provide the demodulated DPSK data stream.

Alternative implementations are presented below. A custom made delay and multiply circuit plus an appropriate clock recovery circuit could be implemented (see Figure 4.3). There are several possible standard clock recovery techniques that are documented in the open literature such as a square law device technique, an early late gate synchronizer, an in-phase/mid-phase synchronizer or even extracting the clock signal from the delay and multiply circuit itself [Ref. 2]. In a delay and multiply circuit, the greatest potential source of error is from the accuracy of the delay element. An offset that is an appreciable fraction of a symbol period will lead to degradation in the probability of error performance of the receiver.

A third possible implementation of the demodulator is to use a standard commercial demodulator for either a QPSK or a BPSK signal. Due to the fact that the data is differentially encoded before transmission, the output of the QPSK or BPSK receiver would not be the original data stream, and as such, "differential decoding" would be required at the baseband output of the demodulator. (For example, if the original data stream was A_k , and was differentially encoded to give B_k according to the rule $B_k = A_k + B_{k-1}$, the the demodulated signal of the QPSK or BPSK receiver would be B_k . The original data stream, A_k , could be recovered according to the rule $A_k = \overline{B_k} + B_{k-1}$.) However, a commercial BPSK or QPSK receiver may not contain a built-in clock recovery circuit, in which case, it would be necessary to purchase a separate clock recovery circuit.

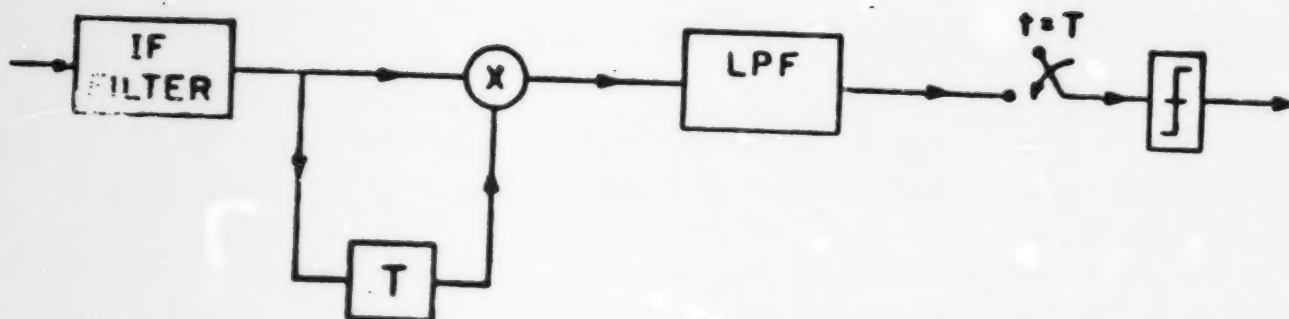


Figure 4.3 DPSK Demodulator

From Figures 4.1 and 4.2, it can be seen that the DPSK demodulator can be configured either before or after the downconverter. If an MLS receiver is employed, then the configuration is fixed (presumably the DPSK demodulator is after the downconverter). If a commercial demodulator is purchased, then the demodulator must also be placed after the downconverter, since the frequency response of available units does not extend to the 5 GHz range of the MLS signal.

If the demodulator is custom made, the RF signal could possibly be fed directly into the DPSK demodulator circuit. However, the required accuracy of the delay element in the delay and multiply circuit, would be greater than current technology can provide. The data rate of the DPSK data is 15.625 kHz, resulting in a baud interval period of $T = 64 \mu\text{sec}$. A current state of the art delay line (Microsonics TV-IH) with a delay of $64 \mu\text{sec}$, has an accuracy tolerance of $\pm 10 \text{ nsec}$. Since the output of the delay and multiply circuit after low pass filtering is:

$$\frac{1}{2} \cos [\theta(t) - \theta(t - T) + \omega_c \epsilon]$$

in which $\theta(t)$ is the signalling phase at time t and ϵ is the offset error of the delay element. Since the frequency of the MLS signal is about 5 GHz, the potential error introduced by the delay error of 10 nsec is $2\pi \times 5 \times 10^9 \text{ rad/sec} \times 10^{-8} \text{ sec} = 100\pi \text{ rads}$, which is unacceptable. Thus, based on the above analysis, it will be necessary to downconvert the RF signal to some intermediate IF (i.e., about 1 MHz) in order to demodulate the DPSK data using a delay and multiply circuit.

4.1.1.4 Amplitude Detector

The function of the amplitude detector is to detect the RF envelope of the scanning beam, which is to be used by the angle processor. Possible implementations of the amplitude detector function include employing an MLS

receiver, using a diode detector, or using a logarithmic amplifier. Both the diode detectors and logarithmic amplifiers are available at the RF frequency of 5 GHz and various possible lower IF frequencies. The critical parameters effecting the accuracy of a diode detector for an MLS amplification are the flatness of the frequency response (typically ± 0.5 dB) and the tangential sensitivity. When using a logarithmic amplifier, the critical parameters are the dynamic range and the flatness of response. The effects of the amplitude device accuracy on the accuracy of the angle processor will be discussed in Section 4.2.3.4 on the angle processor.

4.1.1.5 Frequency Measurement

The frequency measurement of the RF carrier, its tolerance and its stability could theoretically be measured by a microwave frequency counter either before or after the downconverter.

However this is impractical due to the constraints under which the measurement must be performed. Due to the discontinuous nature of the RF transmission, it is necessary to use a "pulse mode" frequency counter. The most appropriate time in which to perform the measurement is during the 832 μ sec. carrier acquisition time slot in the preamble of an function. Since the resolution of a frequency measurement is equal to the reciprocal of the time period over which the measurement was taken, it can be concluded that the best resolution possible within an 832 μ sec. time frame is approximately 1.2 kHz. Furthermore since the internal gating periods of most microwave frequency counters are powers of ten, it is most likely that an external gating capability will have to be provided for the frequency counter to attain the above resolution.

Though the above resolving ability could be considered marginally acceptable for measurement of the RF frequency tolerance, it is clearly insufficient for the measurement of the RF frequency stability.

In order to realize the frequency stability measurements with the required accuracy, it is necessary to measure the RF carrier over a period of several seconds. One possible method of accomplishing this is to perform a special measurement at the transmitter before the RF carrier is modulated. This approach is based on the assumption that the process of modulation does not change the frequency of the carrier. A potential drawback of the above approach is that it requires the manufacturer to provide an auxiliary output port for such a test.

Another potential method of performing the frequency measurement is illustrated in Figure 4.4. This involves tracking the carrier frequency during the 832 μ sec. window and then locking the PLL to this frequency for the period of time required to make a measurement with the resolution needed. The feasibility of the above technique is dependent on the acquisition time of the PLL and the accuracy of the hold circuit for the VCO.

The previous discussion assumes that the measurement takes place before downconversion. Performing the measurement after downconversion would require an accurate measurement of the local oscillator frequencies. A potential advantage is that at lower frequencies, the frequency measurement may be combined with the time interval measurements in the form of a universal counter.

4.1.1.6 Trigger and Function Decoder

The trigger and function decoder is required to read and store the DPSK data coming from the DPSK demodulator. It must be able to synchronize on the 5 bit Barker code in the preamble and identify the function being transmitted according to bits 6 to 12 of the preamble. Having established the timing and the function being received, the appropriate trigger pulses can be provided to the instruments as required to perform a certain measurement.

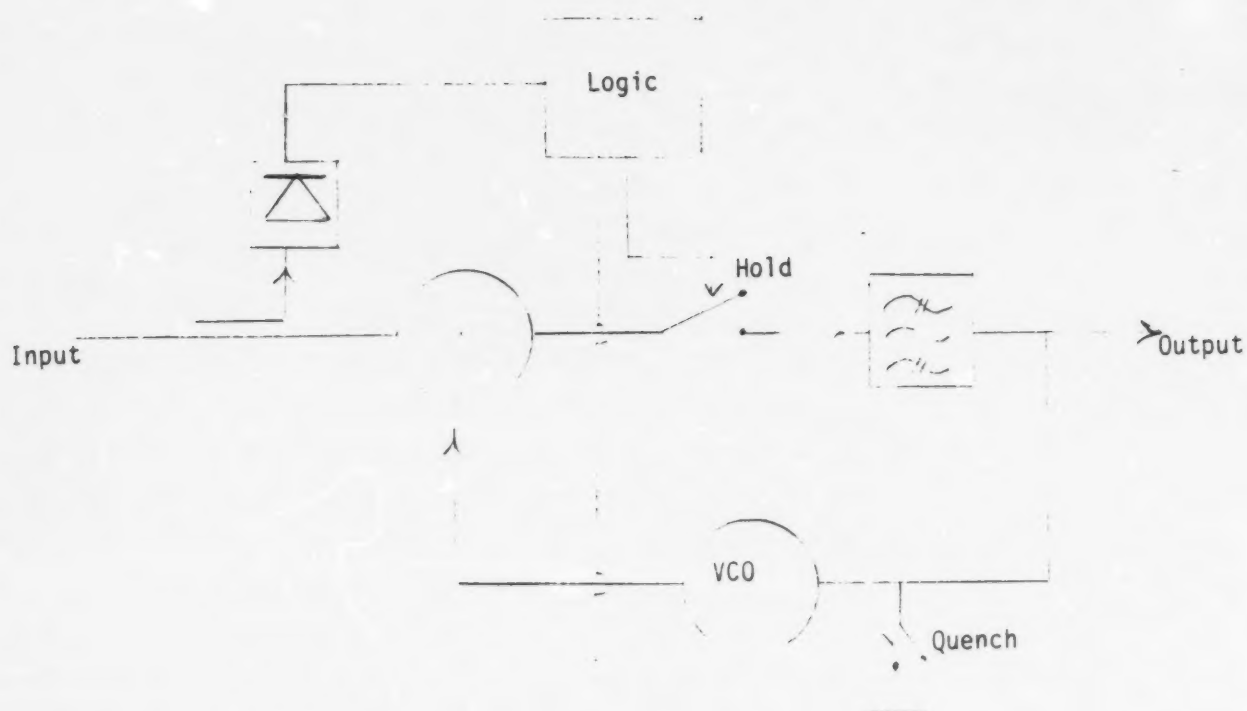


Figure 4.4 Frequency Locking Circuit

One possible implementation for the trigger and function decoder is to use a logic state analyzer. This would permit triggering on predetermined words under software control. Furthermore, most logic state analyzers have a RAM memory usually of the order of 1K to 2K bytes of memory. The potential disadvantage of using a logic state analyzer is that these instruments are designed principally as a hardware debug tool for data systems (i.e., microprocessor based) and as such, are more suited to operate on parallel data, rather than on serial data, as is the case with the present application. Thus, a serial to parallel conversion of the data would have to be achieved prior to the logic analyzer (i.e., by use of a shift register).

Other possible implementations would involve a custom designed delay and compare circuit built by using a shift register implementation. Using a serial shift register approach, there are several possible implementations in order to identify the Barker code, and the function being transmitted. The comparison itself can be done either in hardware (see Figure 4.5) or in software under control of the system controller. A factor in the choice of implementation is that the comparison must be performed in real time (i.e., there is a constraint of 64 μ sec. per bit).

4.1.1.7 Time Interval Measurement

Time interval measurements can be performed using a variety of available instruments such as a universal counter, a digital oscilloscope or a specialized waveform analyzer. Examples of such instruments are provided in Table 4.6. The HP1980 measurement system includes a gated universal counter as well as a digital waveform storage device. This system is capable of measuring such waveform parameters as the period, various time interval measurements, frequency and rise time. It is also capable of storing waveforms with 10-bit resolution, has a programmable trigger flag, and is software programmable via the HP1B. Software packages for various function implementations are available from Hewlett Packard.

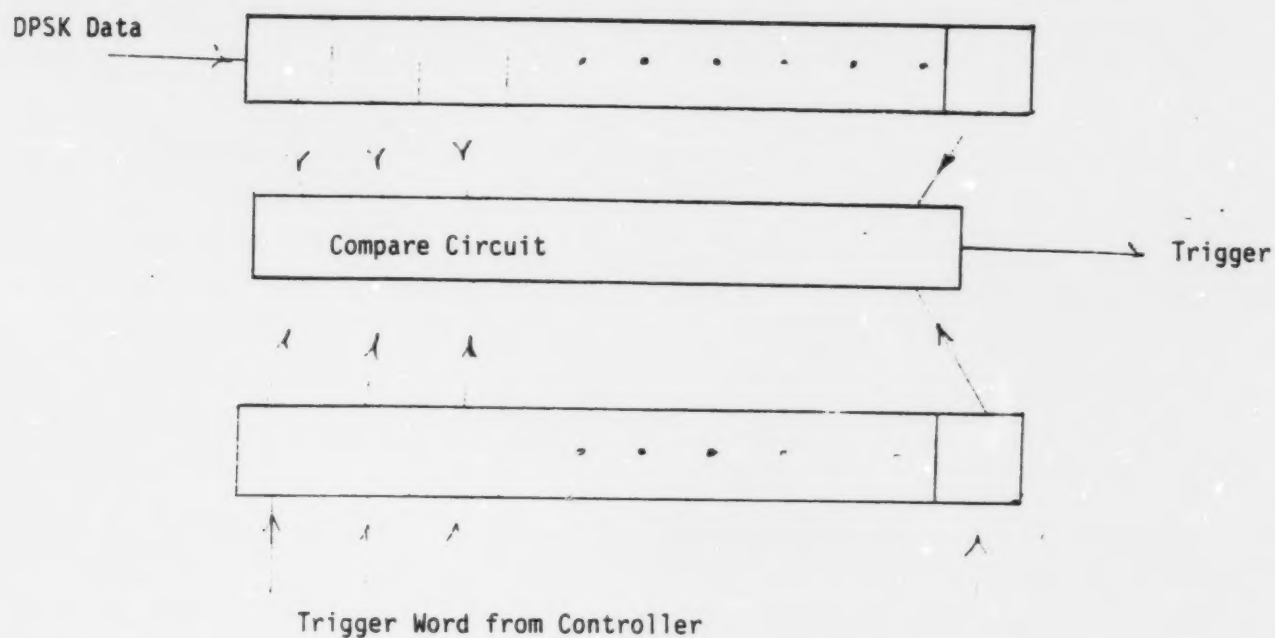


Figure 4.5 Shift Register Implementation of Trigger and Function Decoder

Another possible implementation for the time interval measurement is through use of the HP5180 waveform analyzer. It is capable of storing up to 32 waveforms, has 16K of memory and has a DMA capability for high speed data acquisition. The measurement of the various time interval parameters is achieved by software control. A digital oscilloscope such as the TEKTRONIX 7D20 could also be employed for the above measurements.

Regardless of the instrument used to perform the time interval measurements, the one common feature is the digitizing of the analog waveform and the use of software to perform various time interval measurements. Thus, a final alternative is to simply digitize the entire waveform and store it in memory using a high speed digitizer, then to subsequently perform the time interval measurements in software in non-real time (reducing the complexity of the system). Furthermore, it reduces the dependence of the software packages on the device being used for the time interval measurement (i.e., allowing more flexibility in the choice of the controller and the language in which the software is implemented).

4.1.1.8 Phase Measurements

The static phase error of the DPSK signal must be measured to ensure reliable probability of error performance of the DPSK signal. The ICAO specification states the error in terms of an absolute phase offset with respect to the phase of the RF carrier. (See ICAO Annex 10, Section 3.11.4.4.3.1.) It states that a "zero" (data bit) shall be represented as $0^\circ \pm 10^\circ$, whereas a "one" shall be represented as $180^\circ \pm 10^\circ$. This implies an absolute reference, which is not available as a radiated signal from the MLS system. Thus, a special test set up requiring that the transmitter have a special output port providing an unmodulated RF carrier to be used as a reference. Furthermore, a special data sequence would have to be transmitted for a fixed length of time to give a constant 0° phase output and then a second sequence transmitted to give a constant 180° phase output at the receiver. Note that this measurement would have to be performed before the hardlimiter of the DPSK demodulator. The " 0° phase" and " 180° phase" outputs would be compared to the absolute RF carrier by

using a vector voltmeter. Vector voltmeters are available with the required accuracy of $\pm 1.5^\circ$ or better (see Table 4.7).

It should be noted that the reception of the DPSK data is in fact an noncoherent reception, with no absolute RF reference. Based on a system such as the MLS which does not require an absolute carrier, the ICAO specification 3.11.4.4.3.1 can effectively be interpreted as a relative phase difference of $180^\circ \pm 20^\circ$ between any two consecutively transmitted phase vectors. Under this assumption, the phase difference can be measured with a modulation meter, and an auxiliary output from the MLS is not required.

4.1.1.9 Controller

The controller will be required to initiate (under user control), implement and monitor the tests for any given ICAO specification. The controller will communicate with the test instruments via a GPIB (General Purpose Interface Bus) and in conjunction with the function and trigger decoder, enable the appropriate test instruments and provide the required trigger signal for the specific test being performed. The selection of the specific test to be performed would be selected by the user from a menu supplied in software. Having selected a test, the controller would subsequently trigger on the required MLS function (or sequence as the case may be), activate the required test equipment and monitor the result. Both soft alarms and hard alarms could be used to determine the validity of the performance of the MLS system. Hard alarms would be set at the ICAO specification limit (a violation of which would indicate a system failure) and various soft alarms would be set at intermediate points between the ideal specification and the hard alarm limits. The use of soft alarms in conjunction with the retaining of previous test results would allow the user to determine any degradation in the MLS performance and thus flag the user to investigate potential problems before they actually cause a hard failure.

The memory requirements of the controller will vary with the test system in use (first article, commissioning or periodic) and the extent to which a measurement is performed in hardware or software. The latter factor will also bear upon the ability of the controller to operate in a real time processing mode. However, for reasons of simplicity and reliability of operation, it would be preferable to operate in a non real time processing mode.

Possible implementations of the controller include computers such as the HP series 200 computers (i.e., the 9826) or one of various single board processors available, especially for applications that require real time processing. Other considerations are the requirement for a structured high level language (Pascal, C or ADA) and the requirement for a high speed bus.

4.1.2 SPATIALLY VARIANT PARAMETERS

Two other functional blocks that have been included in the test configuration diagrams are the power measurement and spectrum analyzer functional blocks. It should be noted that these functional blocks deal with spatially variant parameters, rather than to the SIP's discussed in Section 4.1.1. However, since the measurement of power and/or the signal spectrum would be an integral part of any test facility, they have been included here for completeness. Implementations of these parameters are tabulated in Tables 4.8 and 4.9.

4.1.2.1 Power Measurement

The power measurements of the various signal types employed in an MLS system can be measured at several possible points in the test configuration. These possibilities include measuring the power before the downconverter, after the downconverter but before the amplitude detector, and after the amplitude detector. Measuring before downconversion or amplitude detection provides a more accurate measurement, since any errors due to the inaccuracies of the downconverter or the amplitude detector are eliminated.

A peak power meter is necessary, permitting instantaneous power measurements at any point on a signal, by using the appropriate triggering. This feature also allows the power meter to be used as a sampling device, although the data rates required for certain high speed applications may not be obtainable.

4.1.2.2 Spectrum Analyzer

The spectrum analyzer is an optional device in either test configuration of Figures 4.1 and 4.2. Possible uses of the spectrum analyzer include measurement of the residual spectrum, power measurement and downconversion of the RF signal (most spectrum analyzers have an IF frequency output port on the back panel). Limiting factors for use of a spectrum analyzer for the above applications are resolution, accuracy for frequency and power measurements, and the stability and phase noise of the IF output (for use as a downconverter).

4.1.3 OTHER POSSIBLE IMPLEMENTATIONS

Another possible implementation of the test configuration is illustrated in Figure 4.7. In this configuration, a high speed A/D converter is used to digitize the entire incoming RF signal. For such a case, most of the time interval measurements would involve processing the digitized waveforms (increasing the processor speed and memory requirements).

This processing would most likely be performed in non-real time, but preferably by the host processor. Based on the above observations, such an implementation would eliminate the need for the time interval measurement instrumentation (such as the waveform analyzer). Furthermore it also allows simultaneous acquisition of digitized data of the TO and FRO scan needed for angle processing, and dynamic sidelobe measurement. A potential drawback is that the data must be sampled at a constant rate for all measurement applications. As such the sampling rate must be set at that required for the fastest application. This would lead to excess data samples and memory requirements for the other measurement applications.

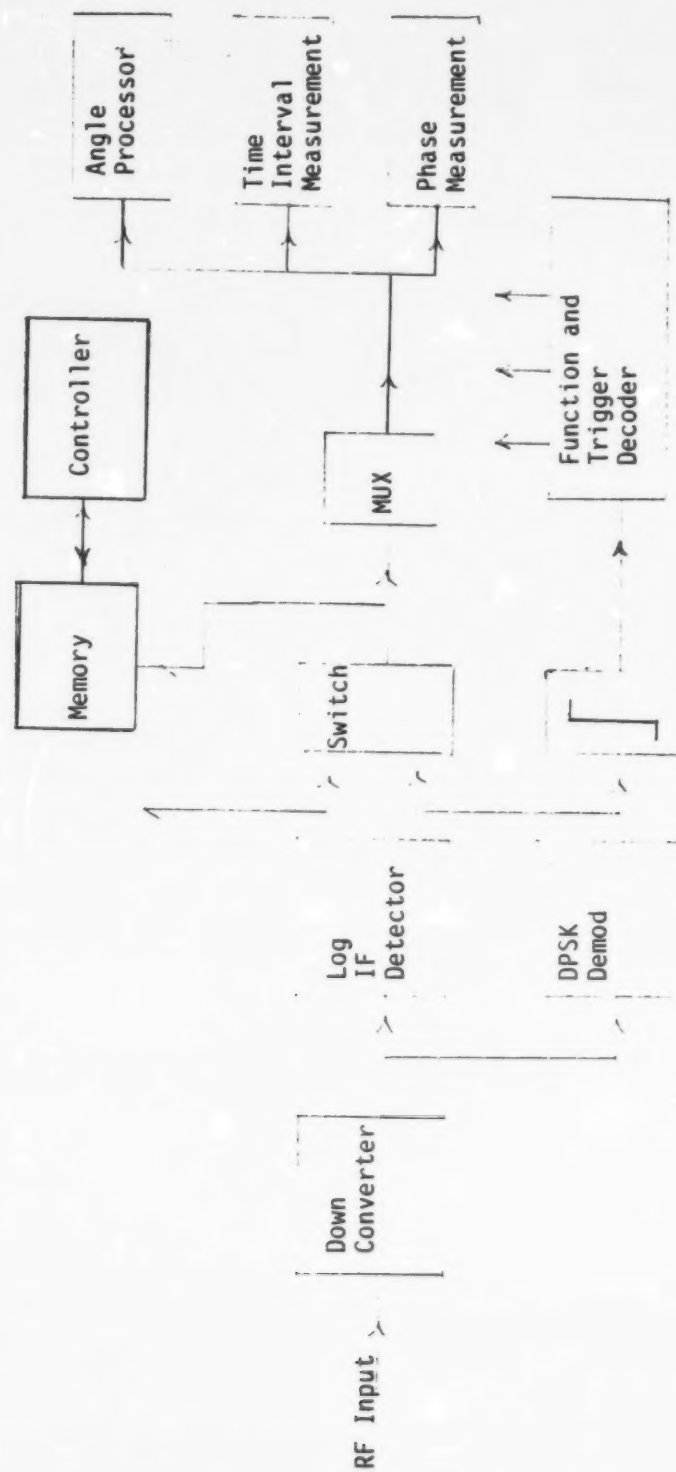


Figure 4.7 Digitized Signals

4.1.4 TEST FACILITY HARDWARE

Tables 4.1 to 4.9, tabulate various possible measuring instruments and hardware that can be employed to implement each of the functional blocks of test configurations A and B.

The controller module could consist of any computer capable of commanding GPIB instruments, such as the HP200 series of computers. The selection of this unit will depend to a large extent on which of the various blocks might be implemented in software rather than hardware since these software tasks would probably be performed in the same computer. Section 4.2.3, for example, will discuss various software implementations of the angle processor module.

Table 4.2 Downconverter

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
MITEQ	Not Available (NA)	NA	NA	single downconversion 160 MHz dual downconversion to 30 MHz log output

Table 4.3 Demodulators

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
AYDIN MONITOR SYSTEMS MODEL 322 + 352 BIT SYNCH.	NA	NA	NA	IF QPSK/BPSK DEMOMULATOR 10 kHz - 10 MHz baud rate 21.4 MHz IF

Table 4.4 Amplitude Detector

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
NARDA	± 1.0 dB flatness ± 0.2 dB over 0.01 - 8 GHz	$\approx 2"$ long 0.25" in diameter	100 mW input max	0.01 - 18 GHz
HP MODEL 503	± 0.2 dB flatness 0.01 - 8 GHz	$\approx 2.4"$ long 0.25" in diameter	100 mW max	0.01 - 18 GHz
RHG LOG AMP ICLX series	± 0.5 dB linearity	4" x 1.5" x $\frac{1}{2}"$	± 12 VDC	If freq. varies from 10 - 200 MHz Bandwidth: 2-50 MHz dynamic range: 80 dB

Table 4.5 Frequency Counters

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
EIP MICRO-WAVE MODEL 451	time base ± 1 count averaging error 6.9 khz to 2 kHz	3.5" H 16.75" W 19" D 30 lbs.	100/120/220 VAC 50-60 Hz	30 MHz - 18 GHz stability 3×10^{-7} /mth resolution 10 KHz PRF: 50 (normal) Hz 0-rear panel selectable sensitivity: -10 dBm peak reading time: 100 mS pulsed mode: GPIB
ANRITSU MODEL MF76A	time base accuracy ± 1 count	133 H (mm) 284 W 351 D 12 Kg	100 V AC 50-60 Hz	0.1 - 18 GHz sensitivity: -22 dBm to ± 10 dBm resolution: 10 KHz with 10 μ s gates 1 MHz with 10 sec. gates acquisition: < 600 mS
HP 5345+ 5356A plug in	≈ 3.2 kHz	132.6 H 425 W 4.95 D (mm) 17 kg.	100/120/220 VAC 48-66 Hz	frequency: 1.5-18 GHz sensitivity: -20 dBm PRF: 50 Hz resolution: 3 kHz Pulse Width: 100 ms to 20 ms
SYSTRON DONNER 6120 D	± 1 count + time base error	NA	NA	freq. 0-26.5 GHz pulsed sensitivity: -20 dBm resolution: 1 KHz

Table 4.6 Logic State Analyzers

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
PARATRONICS INC. MODEL 532	NA	8.9 cm H 30.9 W 36.2 D 4.1 kg	90-240 V 48-440 Hz	5 MHz or 12 MHz clock IEEE 488 32 channels - 250 words storage 1K ram + 8K PROM trigger modes: (i) general parallel, sequential & delayed
HP 1630 A/ D/G LOGIC ANALYZER	40 ns-500 ns	447 D mm 426 W 190 H 13.6 kg	115/230 VAC 48-66 Hz	up to 100 MHz 16 channels 1 K memory HPIB
HP 8182A DATA ANALYZER	5% timing accuracy	178 H mm 476 W 500 D 27 kg.	115/230 VAC 48-66 Hz	8 - 32 channels 1 K memory 50 MHz max. real time compare period: 20 ms-1sec. HPIB
DELAY LINES MICROSONICS TV-1H	64 μ S $\pm$ 10 nsec	NA	NA	BAW

Table 4.7 Time Interval Measurement

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
HP1980 MEASUREMENT SYSTEM +1965 GATED UNIVERSAL COUNTER +19860A DIGITAL WAVEFORM STORAGE	counter: 4.3 nsec	213 W (mm) 508 D 278 H 18.2 kg.	100, 120, 220 V	period: 10 ns to 10 sec resolution = 4.3 μ sec measures freq., period time interval, ratio 19860 - stores two waveforms with 10 bit resolution programmable trigger HPIB 100 MHz scope software packages
HP5180 WAVEFORM ANALYZER + 5182A WAVEFORM RECORDER	NA	142 H (mm) 428 W 574 D 22 kg.	100/120/ 220/240 V	16 K memory (10 bits words) high speed acquisition DMA HPIB 20 MHz timebase
TEKTRONIX 7D20 DIGITAL OSCILLOSCOPE	± 300 -600 psec	NA	NA	40 MHz sampling rate GPIB pretrigger & post trigger signal averaging stores 6 waveforms
TEK WAVEFORMS DIGITIZER 390 AD HP54100	NA	NA	NA	2048 word memory 10 bit resolution BW to 15 MHz GPIB

Table 4.8 Phase Measurement

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
VECTOR VOLTMETER HP8405A	$\pm 1.5^\circ$	177 H mm 425 W 467 D 13.9 kg.	115 or 230 V	1 MHz to 1 GHz phase resolution $\pm 0.1^\circ$ not GPIB 1 kHz BW
HARRIS PRD VECTOR VOLTMETER	$\pm 3.5^\circ$	16.81" W 7" H 16.75" D	115/230 VA	1.5 MHz - 2.46 GHz sensitivity: -40 dBm BW: 1 KHz
HP 8901A MODULATION METER	phase modulation $\pm 3\%$ frequency $\pm 1\%$	190 mm H 425 mm W 468 mm D 20 kg	100, 120 220, 240 V 48-66 Hz	phase modulation 200 Hz - 20 kHz up to 400 rads. deviation
MARCONI MODULATION METER 2305	PM: $\pm 2\%$ FM: $\pm 0.5\%$	152 mm H 425 mm W 535 mm D 13.5 kg.	NA	GPIB 500 kHz to 2 GHz range FM - 500 kHz peak dev. rates or 30 Hz to 275 kHz PM - RF ot 5.5 MHz to 2 GHz maximum deviation: 500 rads

Table 4.9 Power Meters

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
GENERAL MICROWAVE MODEL 478	± 0.3 dB	NA	NA	30 to +15 dBm 0.1 to 26.5 GHz peak power + instant- aneous power PW: 15 nsec to CW IEEE bus calculates rise & fall times & PW - display
PACIFIC MEASUREMENTS INC. RF PEAK POWER METER MODEL 1018B	± 0.3 dB	5.22" H 16.75" W 13" D 16 lbs.	120 VAC 50-400 Hz	20 to +10 dBm 100 MHz to 12.4 GHz PW: 200 nsec. to CW PRF: 0-1 MHz peak and instantane- ous power GPIB bus
MARCONI 6960	+ 0.02 dB	108 mm H 256 mm W	120 VAC	25 ms response time CW, pulsed modes 10 MHz - 18 GHz -70 to +20 dBm pulsed: 0.001 to 100% duty cycle GPIB option
BOONTON RF MICRO- WATTMETER MODEL 4200	≈ 0.05 dB	NA	NA	200 KHz - 7 GHz not pulsed IEEE bus

Table 4.10 Spectrum Analyzer

MFR	ACCURACY	SIZE & WEIGHT	POWER	FEATURES
ANRITSU MS710A	± 2 dB ref. $\pm 5\%$ 200 MHz - 6 GHz $\pm 10\%$ 5 GHz - 1 GHz	177 H (mm) 426 W 451 D 25 kg	100-250 V 50/60 Hz	10 MHz to 23 GHz -115 dBm to +30 dBm GPIB resolution 100 kHz
HP 8559A	$\pm 3\%$ ref. ± 0.5 dB to ± 1 dB	158.8 mm H 501.7 mm W 524.3 mm D	100-240 VAC	0.01 - 21 GHz resolution bandwidths 1 kHz - 3 MHz -111 to +30 dBm
TEK492P				

4.2 RADIATED SIGNAL PARAMETERS

This subsection of the report defines alternative measurement techniques for the MLS signals which will vary spatially, i.e., as a function of the location of the received signal in space.

Four measurement parameters fit in this category:

- Radiated signal power level
- Angle guidance error limit
- Signal polarization effects
- Multipath effects

The spatially variant parameters are discussed under four subject headings:

- Radiation Pattern
- Antenna Requirements
- Receiving Processor
- Multipath

4.2.1 RADIATION PATTERN

The MLS measurement system must be capable of measuring radiated signal power levels and guidance accuracy over an extremely large coverage area (i.e., 80° angular width and 20° angular height out to 20 nautical mile (nm) range as shown in Figures 3.1, 3.2 and 3.3).

The largest single problem with such a measurement is caused by a propagation factor known as multipath. If there are reflecting surfaces located within the antenna radiation field, reflected signals can arrive at a point in space following a multiplicity of paths. The reflected signals cause the radiated signal level to vary significantly because the reflected signal may either add or subtract from the direct signal depending on the phase of the reflection coefficient and the differential path length. A

second propagation factor, rain, is of very little significance because the reduction in signal level is small (less than 2dB) and the rain is unlikely to be localized, i.e., will probably cover most of the coverage volume relatively uniformly.

There are basically two alternative radiated signal measurement techniques which may be applied, Far Field Measurements and Near Field Measurements.

4.2.1.1 Far Field Measurements

The radiating far field region of an antenna is defined as that area where the relative phases and relative amplitudes of the contributions from each of the various elements of the antenna are independent of distance from the antenna. The boundary region where far field performance can be assumed is not well defined, however, the distance $2D^2/\lambda$ is commonly used as a boundary criteria, where D is the largest dimension of the antenna aperture and λ is the wavelength.

For a typical AZ antenna which is about 2 meters long, this far field boundary is 136 meters in front of the array. For a typical EL antenna (about 2½ meters in length) this far field boundary is 212 meters distant.

The major advantage of measurements taken in the far field is that the signal phase front is uniform and the field strength is correct as measured (assuming no multipath). The disadvantage of the far field measurement is the measurement height requirement. For example, at 121 meters from an EL antenna, the field strength must be measured at heights up to 77 meters (250 feet) which is still at the near edge of the far field region. This, in effect, requires far field measurements would have to be made using an airborne test set, either aircraft, helicopter or possibly balloon. Since the purpose of this study was to define a ground-based system, far field measurements are impractical.

It should be noted that far field tests will also be subject to errors in signal strength caused by multipath signals. Therefore, any airborne technique will also have to utilize appropriate techniques to separate direct from reflected signals in order to measure the radiation characteristics.

4.2.1.2 Near Field Measurements

Antenna literature (Ref 4) further subdivides the near field into the reactive near field and the radiating near field with a commonly accepted boundary of about $\lambda/2\pi$ or 9mm (0.4 inches) for MLS. For the sake of the discussion in this report, near field is defined as "a few wavelengths" from the antenna front surface and is, therefore, well beyond the reactive near field region.

The major advantage of near field measurements is that the multipath component can be made zero, since the measurement system can be located closer than the reflective surfaces (usually ground). The major disadvantage of the near field approach is that the near field measurements must measure both amplitude and phase of the signal at a very large number of points over the radiating "surface" and then compute the far field from the measurements. Not only does this involve a very large number of points (for example, if measurements were made every $\lambda/4$ over an antenna 2 m x 1.2 m in size, 12,000 measurements would be required); but the antenna could not be scanned during the measurements since this would change the phase and amplitude measured. Therefore to compute the radiated field in all required directions, billions of measurements would be required, which makes the technique impractical. There is also the additional problem of locating the position of the measurement antenna extremely accurately which is particularly difficult in an outdoor environment. Figure 4.8 illustrates a typical near field test facility (Ref 5) located in Moorestown, N.J.

4.2.1.3 Quasi-Near Field Measurements

As a result of the above analysis, it is evident that practical measurements will have to be made in the quasi-near field, that is sufficiently inside the far field boundary to make use of a practical size

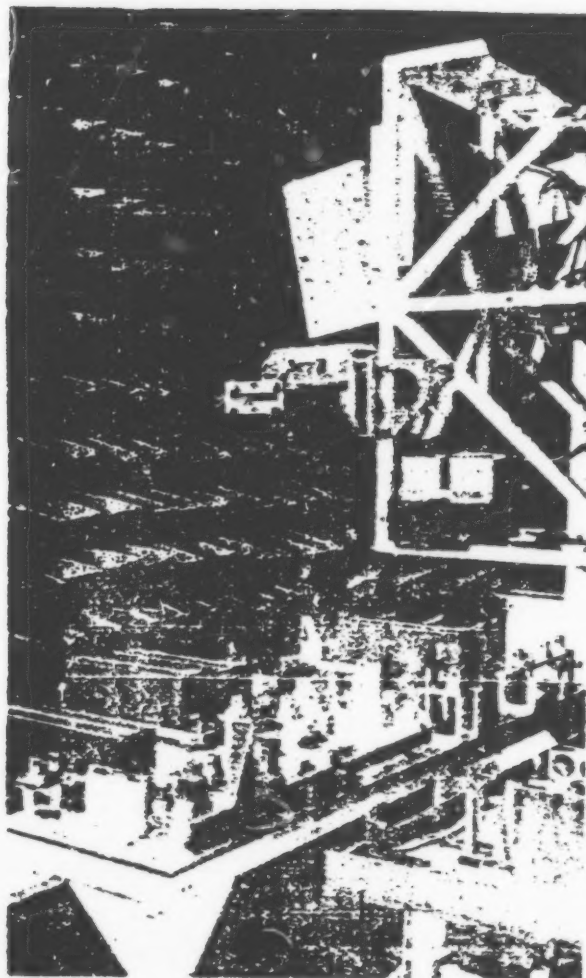


Figure 4.8 A Laser-Based Near Field Measurement System
(Courtesy of RCA)

erectible tower as a measurement support. In order to assess the performance of such a quasi-near field probe, an analysis of the radiated signal levels in this region was made.

A FORTRAN computer program was written which used the law of cosines (see Appendix B for details) to obtain the phase path length between each of the elements and the probe antenna. For comparison, the phase path difference between elements was also calculated assuming that the probe antenna was an infinite distance away. The calculations were made assuming an array 1.56 meters wide with 64 elements and a Taylor weighting to achieve a 2.2° beamwidth and a 30 dB sidelobe levels. Using the "law of cosines" calculation for distances of 38 meters (125 ft.), the equation yields a pattern which differs from the pattern assuming an infinite distance; i.e., the main beam of the antenna increased in width at its base and the nulls between side lobes changed appreciably. While the beam was slightly broadened, any algorithm which would determine the beam center in the far field case could still be expected to give valid results in the quasi-near field. Larger apertures (i.e., narrower beamwidths) would show more pattern degradation for the same separation distance.

The plots of Figures 4.9, 4.10 and 4.11 show the effects of quasi-near field (38 m. distance) and far field measurements on the beam pattern as measured with a 60 cm. (2 ft.) diameter antenna, illuminated with a $(\cos)^{1.3}$ distribution. Figure 4.9 illustrates the effect on boresight. The gain is reduced by only 0.18 dB and the beam spreading is insignificant down to about -10dB below the main lobe. Figures 4.10 and 4.11 show the off-boresight effect at 30° and 60° off normal. At 60° , the far field beam is spread (as normally expected) by an amount proportional to $1/\cos \theta$ (where θ = off-normal angle) but the effect on the beam pattern due to the quasi-near field distance has become almost negligible.

As the probe antenna is moved away from array normal, the antenna aperture appears shorter when viewed from the probe antenna. This decreases the pattern degradation caused by the shorter path length between array and probe antenna. However, some beam squint develops, caused by the short path length between antennas. The beam center line for the short path deviates from the beam center line for the infinitely long path, as the beam scans away from either side of broadside. This is not considered to be a serious problem because the beam deviation is small so the magnitude can be computed and a correction made for it. The deviation is a minimum at broadside and endfire conditions because of symmetry and a maximum at about 45° . It occurs because the "near field" phase error is slightly less for the farther half of the antenna than it is for the nearer half.

Figure 4.12 shows the calculated beam squint for the antenna as a function of the distance to the probe antenna and the angle from boresight. It can be seen the maximum angular error equals $.0170^\circ$ at 15 m. (50 ft.) distance, which is becoming significant. Therefore, distances of 30 m. (100 ft.) or more should be used if possible, otherwise corrections may have to be made.

The effect of using a probe antenna of finite size can be compared to a point source type probe antenna instead as shown in Figure 4.13 for both far field conditions and distances of 38 m (120 ft.)

4.2.2 ANTENNA REQUIREMENTS

A quasi-near field probe should ideally be an isotropic (point source) antenna in order to minimize the probe's influence on the measured signal. However, two practical difficulties are immediately clear.

The first is that signal measurement errors may be caused due to signals reflected off the tower structure. The tower could be covered with an absorbing material to solve this problem, however, this would be difficult to accomplish on a telescoping tower. A more practical technique would be to use dipole antennas spaced at one-quarter wavelength to create a cardioid pattern with the tower in the null.

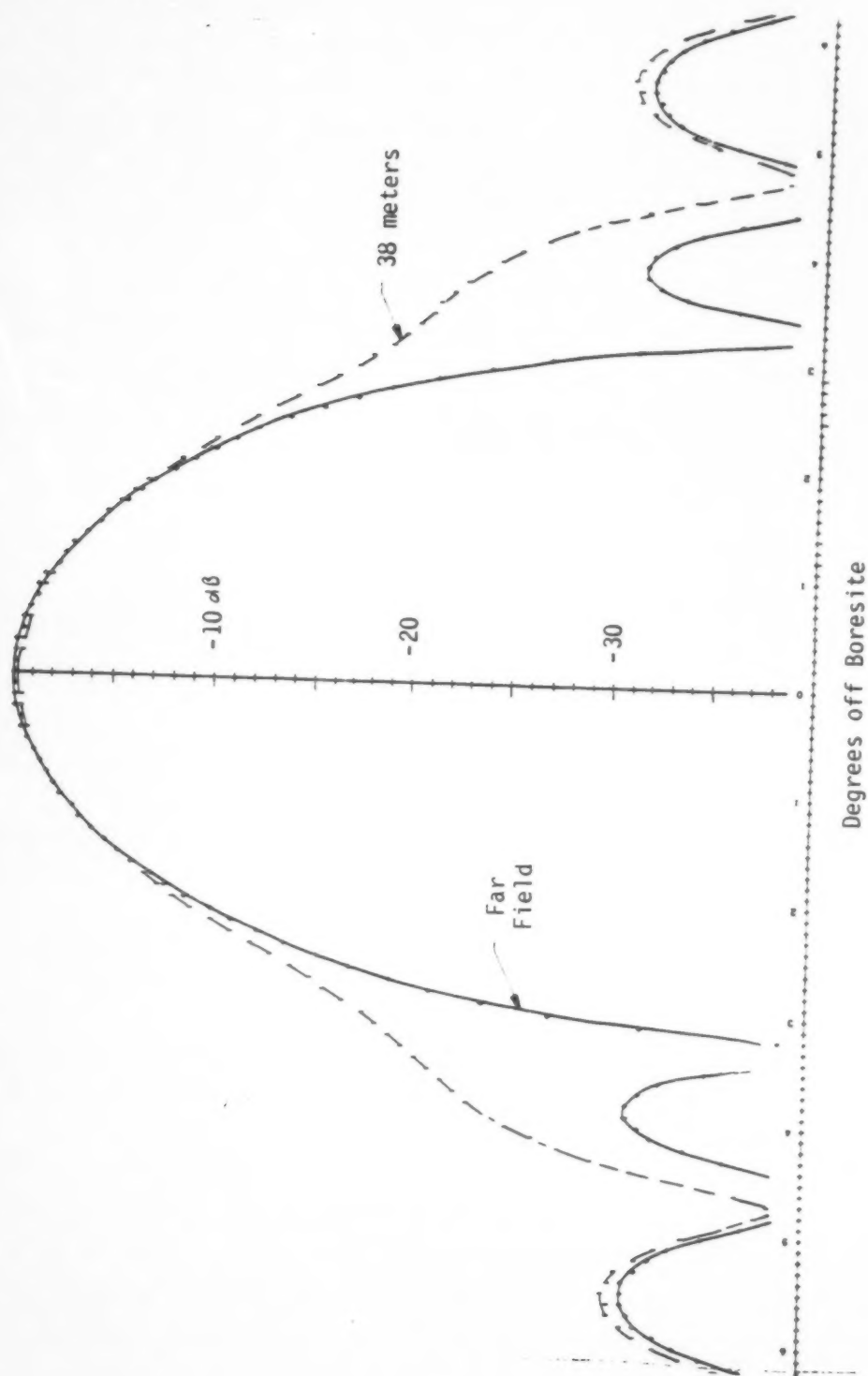


Figure 4.9 Far Field/Near Field Comparison on Boresight

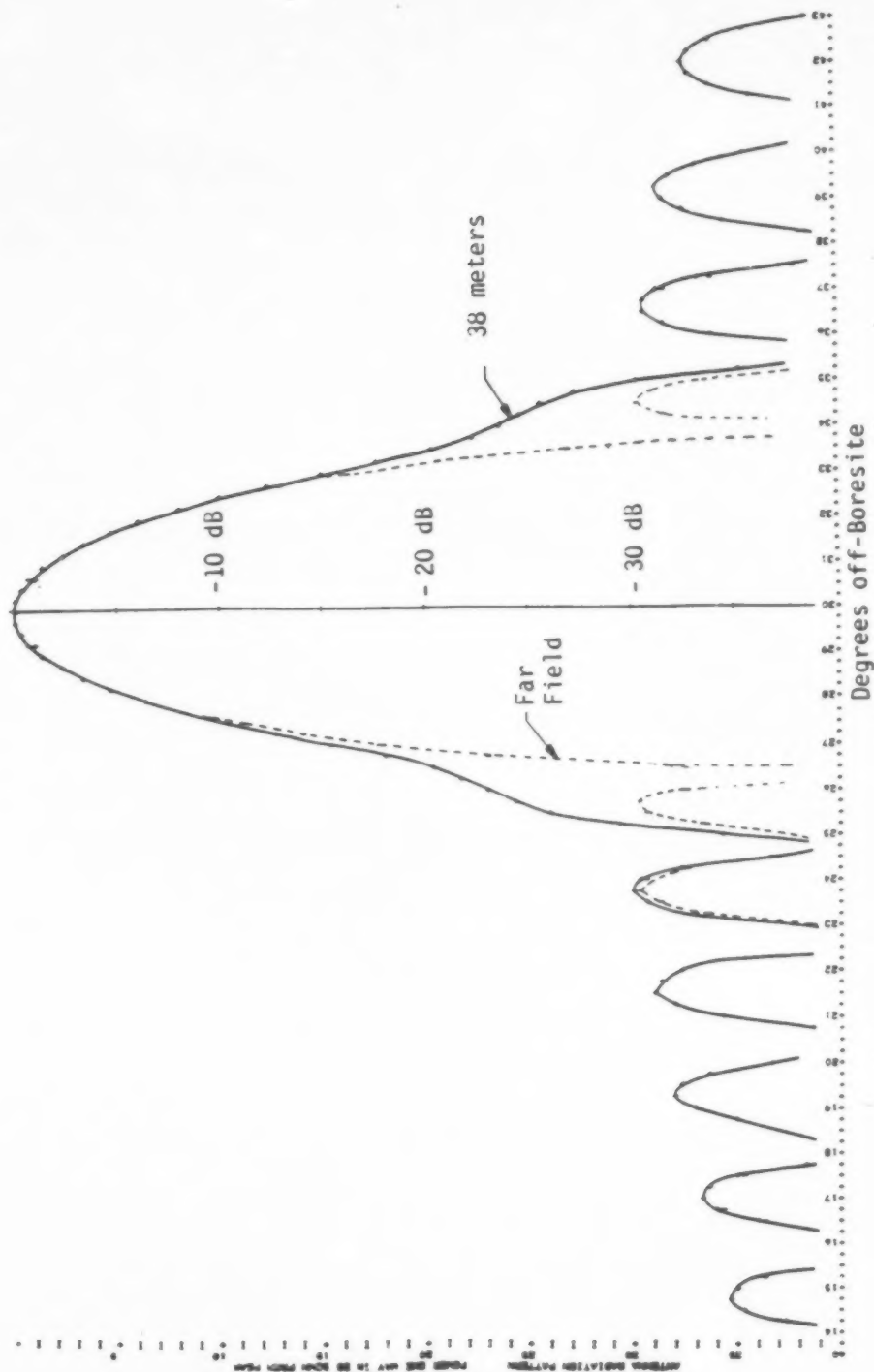


Figure 4.10 Pattern 30° Off-Boresight

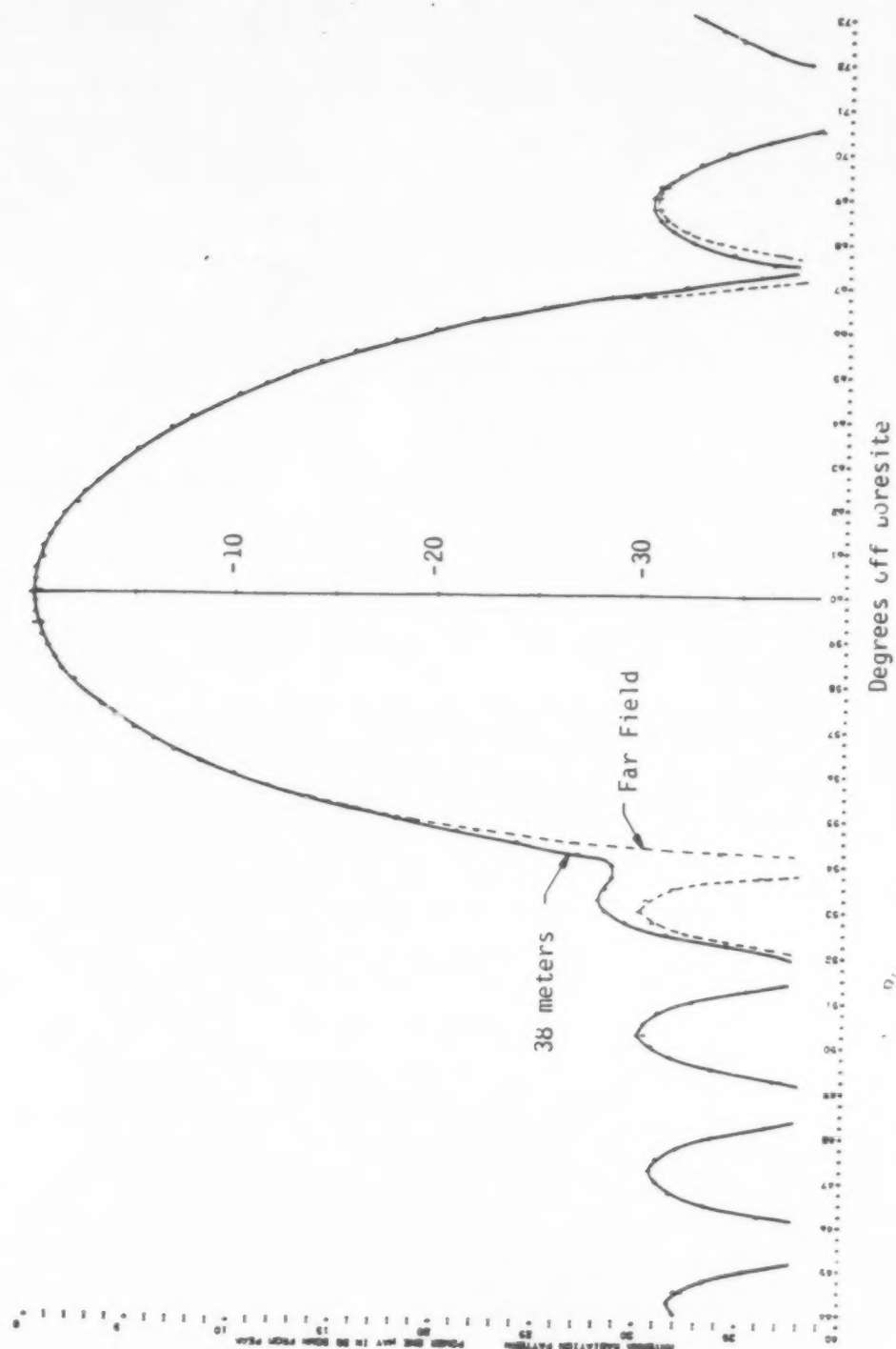


Figure 4.11 Pattern 60° Off-Boresight

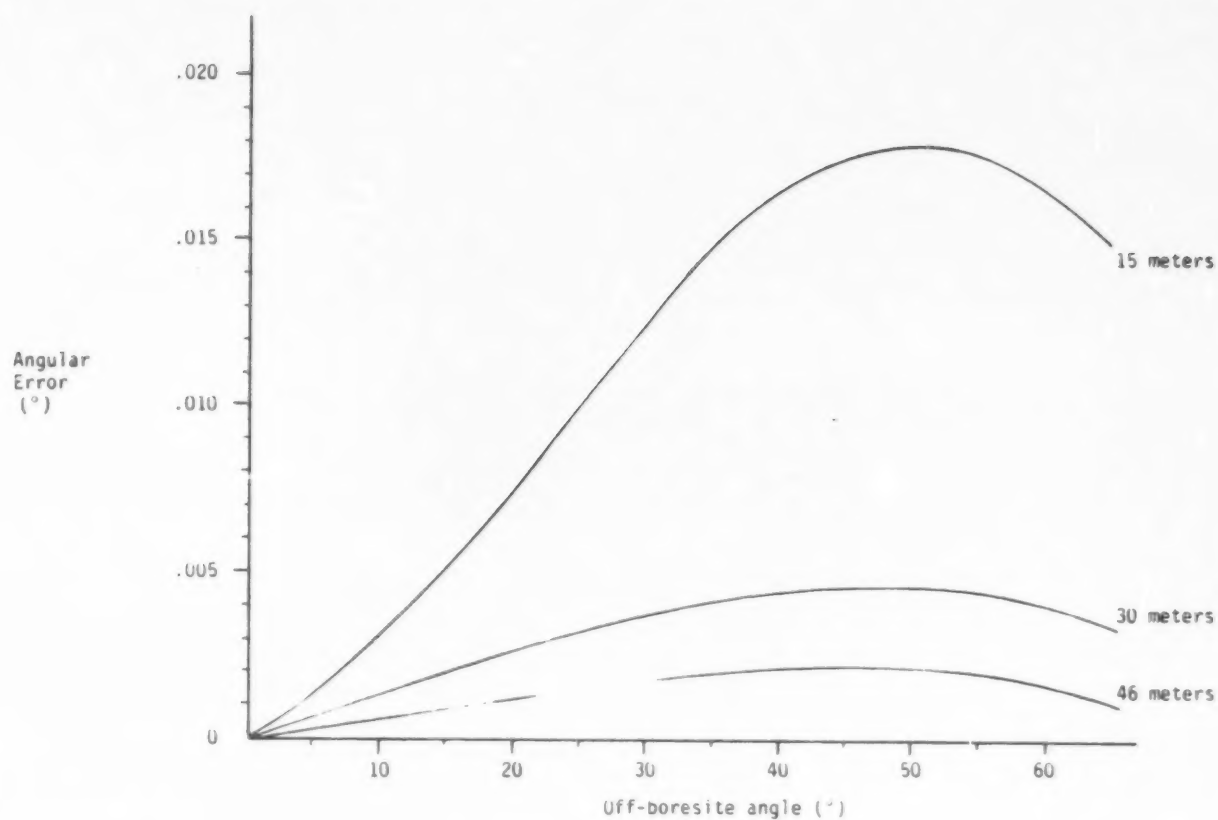


Figure 4.12 Beam Squint for Quasi-Near Field Distance

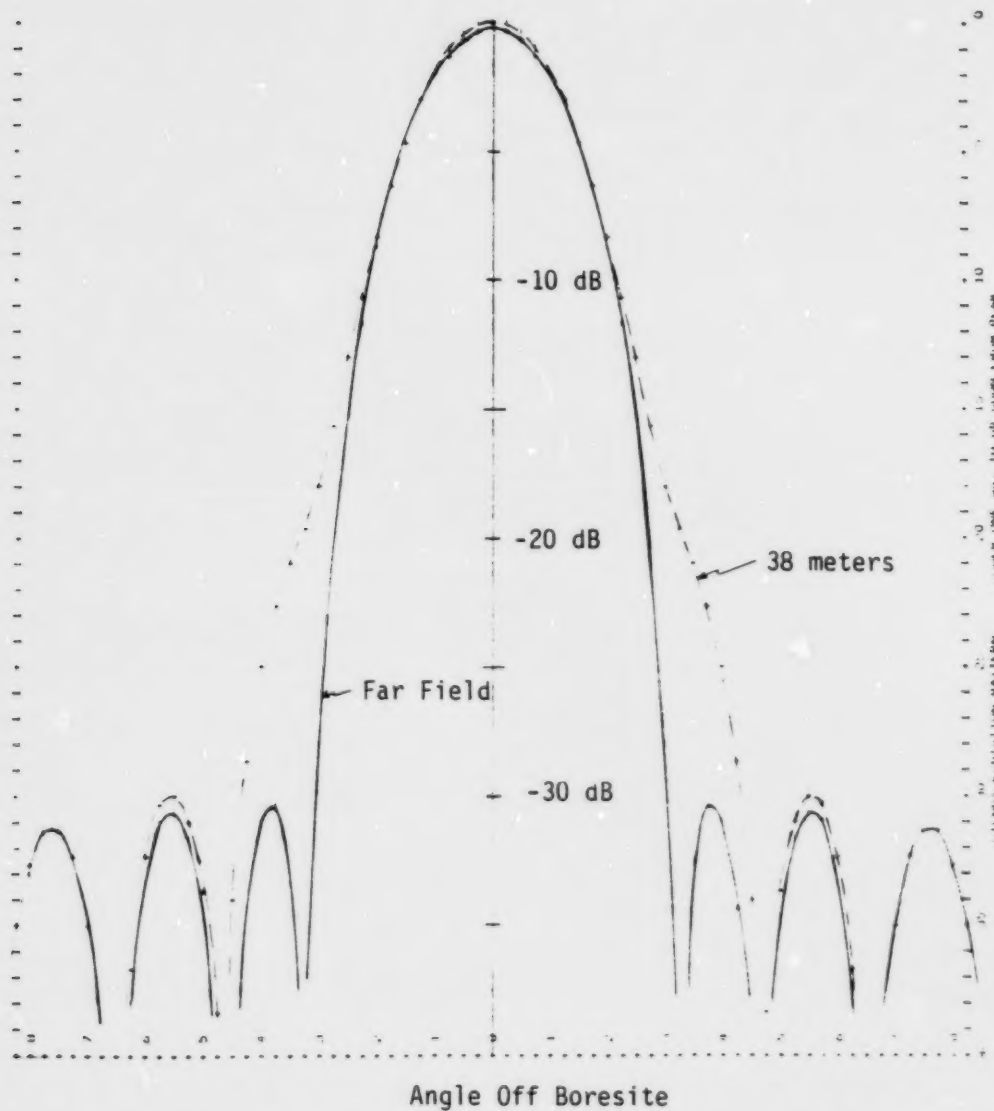


Figure 4.13 Point Source as Probe Antenna

The second problem, much more difficult to solve, is due to reflections off the ground between the MLS system and the field probe.

4.2.2.1 Ground Reflected Multipath

Before this problem is analyzed in detail, it is desirable to discuss why reflected signals create a problem. The first reason is, in order to meet an ICAO specified performance limit, the measurement system is required to be capable of measuring the MLS system guidance accuracy in an environment free from propagation effects such as multipath. The second reason is that reflectors which serve as the source for multipath signals can cause multipath signals which vary in magnitude at different points in the coverage volume. As a consequence, measurements made close to the MLS cannot be used to predict performance elsewhere in the coverage zone in the presence of multipath. Therefore, reflections should either be removed or reduced to the point where resulting errors are insignificant. Ground will be the predominant source of multipath close to the MLS.

Ground reflection measurement affects can be minimized in three ways:

- i) Highly directive probe antenna
- ii) Measurement and subtraction of reflected signals
- iii) Addition of absorbing material or diffraction fences

a) Directive Antenna

A highly directive probe antenna can be used to discriminate against ground reflections. The antenna must be quite large to achieve this directivity, which is disadvantageous because of increased wind resistance. The optimum diameter antenna for probing the MLS field involves consideration of several factors. The antenna must be small enough so that it can be supported on the tower with minimum movement caused by wind. For the highest peak and sharpest signal fall off, the illumination of the probe antenna should be the same as the incident beam from the MLS antenna, since this problem is similar to the matched filter problem where the filter response should be the same in frequency as the anticipated received signal. Although a delta function response (i.e., a point source antenna) exactly reproduces the received signal and the overall signal response is not stretched out, a matched filter produces a response of greater magnitude. It is proposed that the probe antenna selected should have a diameter no greater than that equivalent to the 10 dB points of the incident beam at the shortest distance anticipated for measurement. Second, the shape of the illumination pattern across the parabola may not be perfectly symmetrical and the apparent shape of the received beam would be modified. This change in shape, commonly called skew, will make it more difficult to accurately locate the centre of the beam.

b) Reflected Signal Measurement

It is also theoretically possible to measure the amount of the ground reflected signal in space and then subtract the reflected signal portion from the measured signal. This approach requires a considerable increase in the number of measurement points and computations to obtain the reflected and direct portion from the measured result.

This measurement technique has been successfully used to accurately measure radiated power. However, the impact of ground reflection on guidance signal accuracy can be much more significant, depending on the reflection surface characteristics. A successful approach would require averaging of a large number of measurements. A more detailed analysis would be required to prove if this technique could be made sufficiently accurate and practicable.

c) Absorbing Material/Diffraction Fence

Reference 6 describes two successful techniques for reducing the effects of multipath. One method involves the addition of a metallic or absorber covered fence or fences to block the reflected signal path. A second technique is to provide a "mattress" or layer of RF absorptive material on the ground in the reflection area thereby reducing the reflected signal.

4.2.2.2 Antenna Location

The location of the probe antenna within the quasi-near field zone is not particularly critical for measurements of radiated power. However, measurement of guidance angle accuracy requires that the phase centre of the probe antenna be located very accurately. For example, Table 3.19 defined the ICAO accuracy requirements as $\pm 0.05^\circ$ PFE, $\pm 0.017^\circ$ CMN for a 10,000 foot runway. (Note that the $.017^\circ$ CMN is recommended, not mandatory.)

In order to determine whether the achieved guidance accuracy is within this bound, a measurement of accuracy of at least $\pm 0.01^\circ$ is recommended. Assuming an equal error contribution by the receiving processor, an antenna positional error less than $\pm 0.005^\circ$ is therefore desired. For example, at a distance of 42 meters from the MLS, this translates into a positional accuracy requirement of ± 3.7 mm (± 0.14 inches) for the probe antenna. From the point of view of absolute position, this grade of accuracy is readily achievable with a theodolite. However, at the top of a 15 meter (50 foot) nonguyed tower, wind induced vibration will almost certainly cause this motion bound to be exceeded.

Therefore, an antenna tracking system will be required, with the output of the tracker to be fed into the receiver processor to be subtracted from the measured guidance position.

There are several different techniques available for tracking the expected antenna motion, three alternative methods are proposed and discussed below:

- Manual Optical Tracking
- Accelerometer Approach
- Automated Optical Tracking

a) Manual Optical Tracking

This technique requires a digital encoding theodolite to be used to manually track the probe antenna. The use of this technique would be predicated on the antenna motion being at a sufficiently low frequency that the human reaction time would be sufficiently fast to track the motion accurately. Since Control Motion Noise (CMN) includes frequencies up to 1.5 Hz, motion components up to 1.5 Hz would need to be tracked. While this would not be considered impossible, it would be very demanding.

b) Accelerometer Motion Detection

If an accelerometer were mounted between the antenna and the tower, the varying component of the antenna motion would be measured. Using the acceleration measurement and an accurate model of the antenna subsystem, it would be possible to compute the velocity and displacement of the antenna. (The mean location of the antenna would have to be found by other means, for example, a theodolite.)

The major advantage of this approach is the fact that tracking is automatic. The major disadvantage is that the location is computed from acceleration, hence, unless the motion is reasonably fast and reasonably symmetrical about the user position, the accuracy would deteriorate as a function of time. A more detailed analysis would be essential before this location technique could be recommended.

c) Automated Optical Tracking

This approach requires an optical system which tracks the motion of the probe antenna based on either a laser or a non-coherent light source, with the light source mounted at the phase center of the antenna.

One technique would be to focus a Closed Circuit TV (CCTV) camera on a light source mounted on the antenna and then, by means of an image tracking algorithm, locate the x-y coordinates of the light source thereby providing position information. While this technique suffers from the disadvantage that optical distortion in the lens translates into an error in location, it is possible to measure the error and compensate for it in a suitable post processor.

Alternatively, to avoid a requirement for a high quality lens, the lens and camera could instead be mounted on a servo-controlled positioner. The system would then be operated in a closed loop mode where the servo would always aim the lens so that the light image was located in the centre of the camera image.

It should be noted that only one-dimensional tracking is required, i.e., horizontal tracking for the AZ antenna and vertical tracking for the EL antenna, since motion in the other planes will not produce a guidance error.

4.2.2.3 Polarization Effects

The ICAO specifications require that the guidance accuracy be maintained while the receiving antenna is rotated off-vertical polarization by an angle of 30° . Therefore, the vertically polarized probe antenna must be mounted such that rotation by $+30^\circ$ and -30° is achievable.

4.2.2.4 Interferometer Antenna

Some consideration has been given to using a twin aperture interferometer type probe antenna. Such an antenna system will give a very sharp difference null as the MLS beam scans past it. The advantage of this approach is that the 2° beam is dramatically reduced in width. Therefore, the accuracy of the location of the beam centre could be significantly increased.

The technique involves the vector subtraction of the output of two antennas to produce a difference pattern (often referred to as monopulse) with a very sharp null midway between the antennas.

The spacing of the two antennas for this particular application must be less or equal to one beamwidth, in order to produce a sharp null. In order to determine the shape of the expected response, the system was modelled, using two 60 cm. (2 ft.) diameter parabolic dishes spaced at 91 cm. (3 ft.) centers (equivalent to 1.4° at 38 m. (120 ft.)). The 2.2° beam model previously defined was used as a source and the twin aperture antenna sum and differences were plotted as a function of angle as the beam swept past the boresight location. This output is plotted in Figure 4.14. The difference pattern shows a very sharp deep null as expected.

Assuming that the processor beam centre finding accuracy is, in fact, inversely proportional to beamwidth, this technique is obviously of great advantage. However, there are also disadvantages as well, mostly due to the added complexity of the antenna structure.

4.2.3 RECEIVING ANGLE PROCESSOR

The function of the receiving angle processor is to calculate the angular position of the receiving platform (i.e., the aircraft under normal operating conditions, or the mobile test facility under test conditions) with respect to the boresight of the ground MLS antenna (azimuth, elevation or back azimuth). The estimation of this angular position is determined by the information provided by the "TO" and "FRO" scanning beams of the MLS antenna. By definition, the angular position is calculated from the time separation between the centers of the received "TO" and "FRO" scanning beam mainlobes by the equation (see ICAO ANNEX 10, para. 3.11.4.5):

$$\phi = (T_0 - t) V/2$$

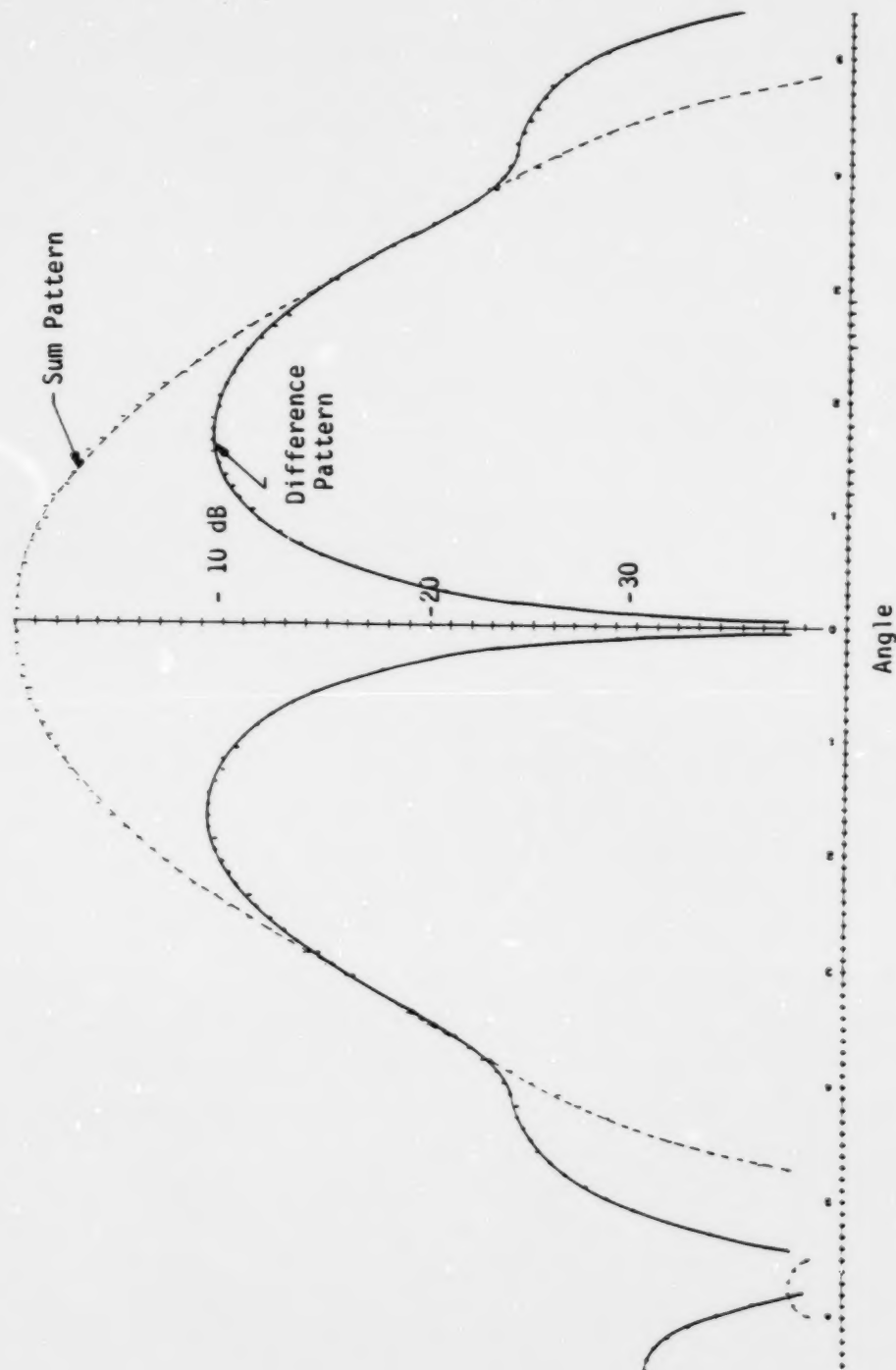


Figure 4.14 Interferometer Antenna at 38 Meters Distance

in which ϕ is the guidance angle in degrees, t is the time separation in microseconds between the TO and FRO beamcenters; T_0 is the time separation in μsec between the TO and FRO beamcenters corresponding to zero degrees, and V is the angular scan velocity (1° per $50 \mu\text{sec}$). Figure 4.15 illustrates a typical aircraft scenario and the resulting video waveforms. The ICAO definition of beamcenter is the midpoint between the two -3dB points on the leading and trailing edges of the scanning beam mainlobe. [ICAO Annex 10, para. 3.11.1].

A ground test facility receiver offers several intrinsic advantages over that of an airborne receiver. The most significant of these advantages is that the test receiver unit can remain stationary in space over many scans if required. This allows the receiver time to gather statistics concerning the errors introduced by various types of impairments. These statistics can be exploited to obtain an improved angle processor.

There are several alternative techniques for estimating the beamcenter, for example:

- a) determining the centroid of the mainlobe
- b) correlating the received beamshape with an idealized waveform
- c) least mean square estimation of beam center

When "a priori" information on the statistical variation of the beam characteristic is available, this information can be utilized to minimize the error. This error can be minimized using one of several possible error criteria, such as sign magnitude, absolute value or least squares. The minimum least squares error criteria will be discussed primarily because its performance does not degrade easily.

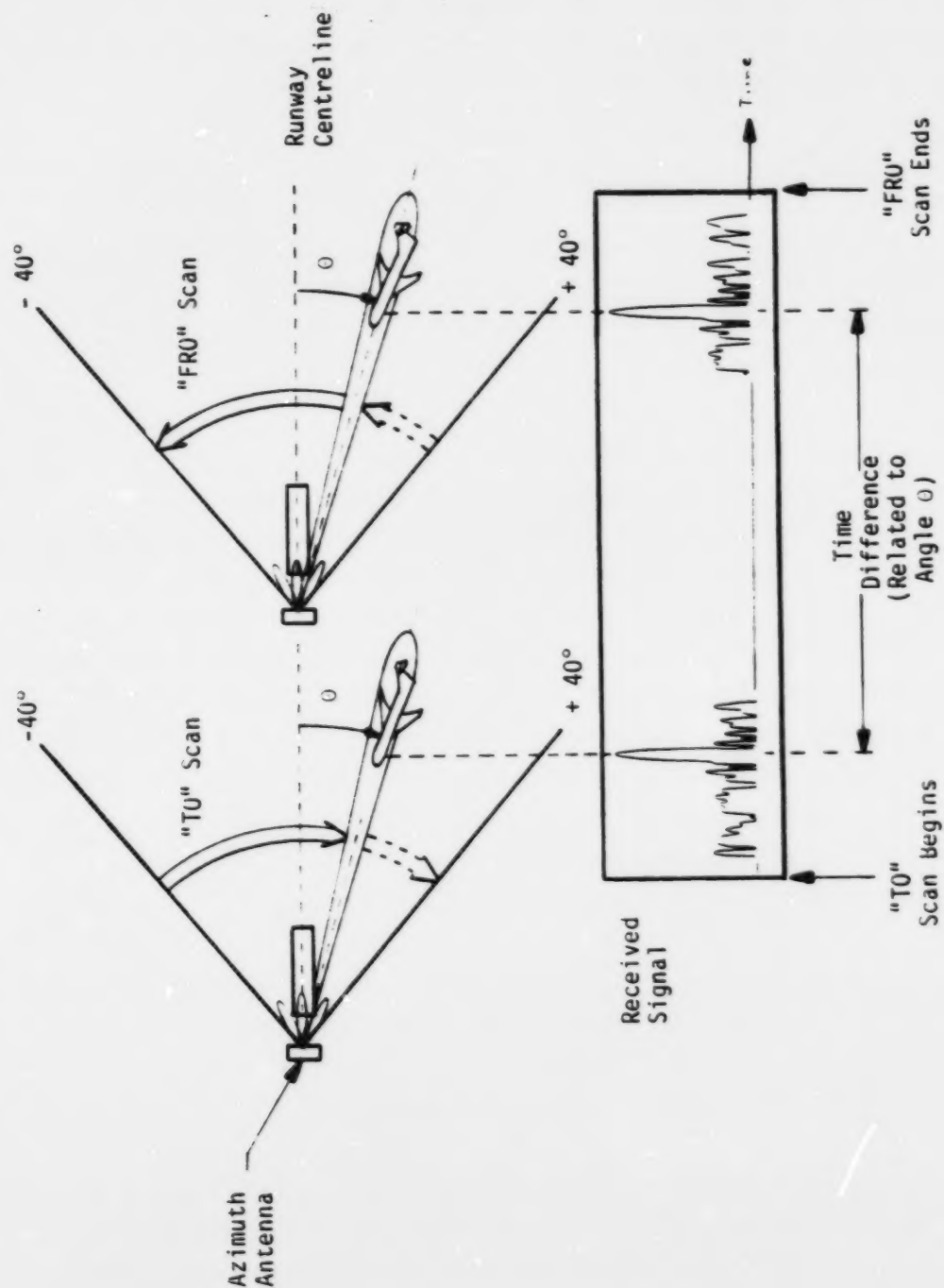


Figure 4.15 MLS Receiver Waveforms

These algorithms will be considered in light of their technical feasibility (i.e., sampling rate required, memory requirements, and processing requirements) and the accuracy of the algorithm.

4.2.3.1 Centroidal Line Method

The centroid method involves integrating over the entire mainlobe and determining the area under the mainlobe. The centroid of the beam is defined as the line which divides the mainlobe into two regions of equal area (see Figure 4.16).

Conceptually, this algorithm could be implemented in either an analog or a digital fashion. An analog implementation is illustrated in Figure 4.17. The input scanning beam would be passed through an integrator to calculate the total area under the main beam. This output is divided by two and held as a reference input for the comparator. A second delayed version of the scanning beam (the delay T is assumed to be greater than the width of the main lobe of the scanning beam, which is typically 100 μ s) is also integrated, and its output fed into the comparator. When its output exceeds the reference voltage of the comparator, the comparator output will provide a trigger indicating the center of the TO or FRO beam (i.e., a trigger to be used to start and stop a timer that measures the time difference between the center of the TO and FRO beams).

Based on the fact that 1° of beamwidth is equivalent to 50 μ s, and assuming that the error contribution due to the clock must be less than 0.001° , then a timer with a clock rate of at least $1/(50 \times 10^{-6} \times 0.001) = 20$ MHz would be required.

Potential problems with the above analog approach include the problem of triggering the main lobe integrator so that it only integrates the main lobe (i.e., determining the start and stop points of the main lobe) but excludes sidelobes. A threshold level would have to be determined in order to define these start and stop points.

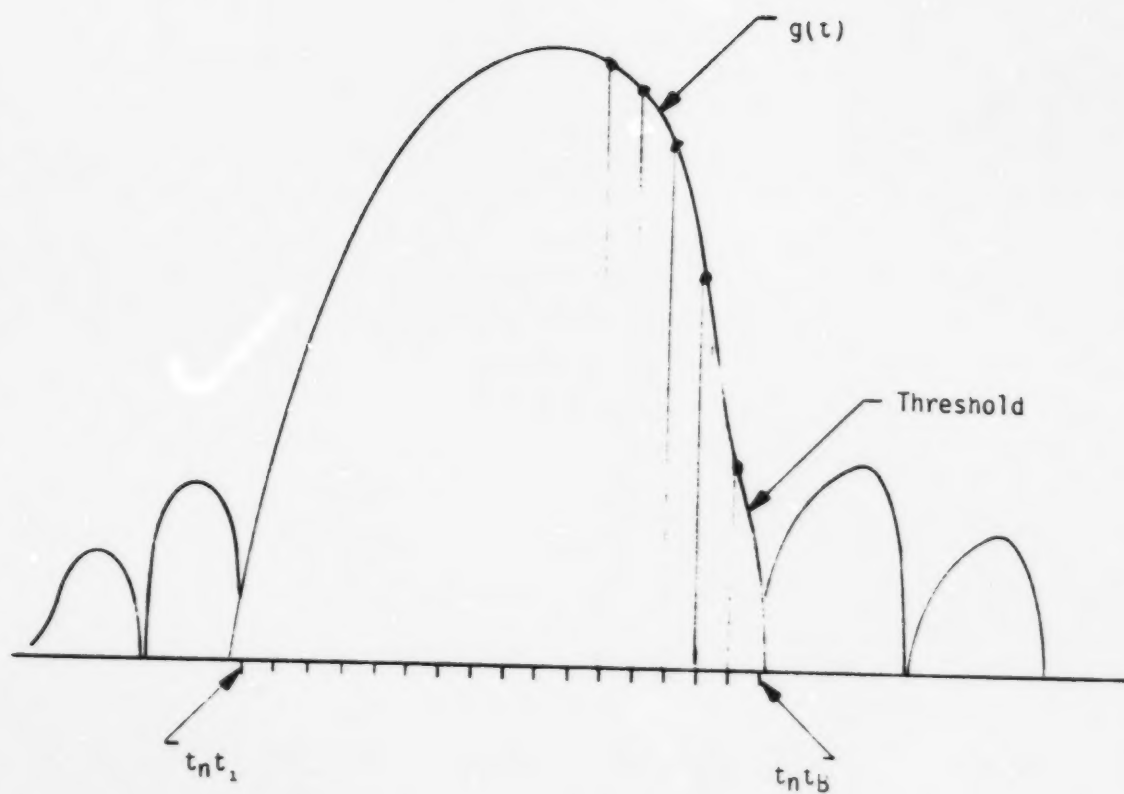


Figure 4.16 Centroid Method

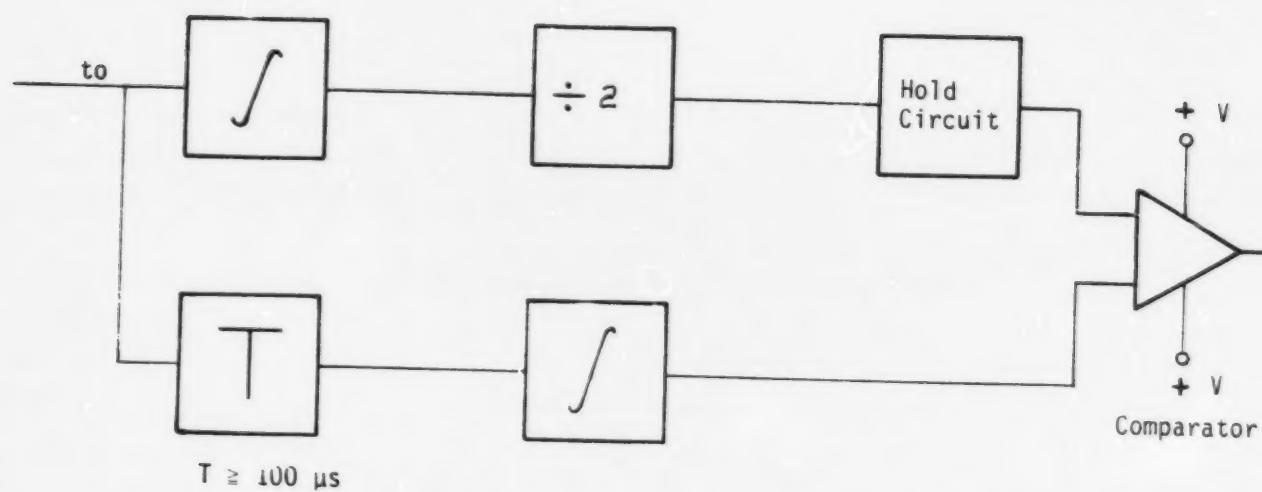


Figure 4.17 Analog Centroid Method

The centroid locating algorithm could also be implemented digitally. Referring to Figure 4.16, the mainlobe is sampled (see Section 4.2.3.4 for a discussion of digitization considerations, such as required sampling rates, aliasing, quantization errors, etc.) at equally spaced points in the time domain, giving corresponding amplitude values of the beam. With regard to the above sampling, a criteria must be selected which defines the start and stop times of the main lobe. Possible criteria include using an amplitude threshold (any samples below this threshold are not considered as part of the mainlobe), or sampling within a predefined window (centered about the mainlobe) in the time domain.

The sampled values of the mainlobe would be stored in an appropriate memory. From these stored values, the processor would be required to integrate the area under the mainlobe by using one of several possible standard numerical integration techniques. For example, a "Gauss Quadrature" type integration would produce accurate results with a minimal amount of computation required. While it is assumed that the function defining the shape of the mainlobe is well behaved, (i.e., high frequency variations are not a significant problem), the process of integrating will tend to "smooth" the effects of the high frequency variations. It should be noted that numerical integration necessitates interpolation between the collected data points. Possible interpolation algorithms include a simple first order (linear) interpolation, a second order interpolation (parabolic), or other higher order interpolation methods (such as a "cubic spline") (Ref. 7).

In more formal terms, let the amplitude of the mainlobe be defined by the function $g(t)$, over the region the interest $[t_A \leq t \leq t_B]$. Furthermore, let $G(t)$ be defined by:

$$G(t_A, t_B) = \int_{t_A}^{t_B} g(x) dx$$

The center of the beam " t_C " would then be defined by the relationship:

$$G(t_A, t_C) = \frac{1}{2} G(t_A, t_B) = \int_{t_A}^{t_C} g(x) dx$$

From the above equation, there are several possible algorithms to determine t_C . One approach is to use a running integration, (i.e., starting at t_A and stopping when the integral equals $\frac{1}{2}G(t_A, t_B)$), with an appropriate integration method such as the "trapezoidal" method or "Simpson's" method. ("Gauss quadrature" integration is not applicable since it requires unequal spacing of the sample points.)

An alternative algorithm would be to employ an iterative process, as is illustrated in Figure 4.18. Initially, an estimate of t_C is employed. The error ϵ between $G(t_A, t_C)$ and $\frac{1}{2}G(t_A, t_B)$ is used to readjust the estimate of t_C . If the error is less than a predetermined threshold Y (for an angular error less than 0.001, Y would be set at $\approx 50 \times 10^{-6} \text{ sec/}^\circ \times 0.001^\circ \times g_{\max}(t) \approx 50 \times 10^{-9} g_{\max}(t)$), then the algorithm would stop, whereas if the error ϵ was still greater than the threshold Y , the algorithm would continue for further iterations.

4.2.3.2 Correlation Method

A second alternative method of locating the beam center is by using a correlation technique. Basically, this technique involves generating an ideal theoretical waveform and correlating it with the received waveform. The ideal waveform is "slid" past the received waveform (see Figure 4.19) and the point of the ideal beam center corresponding to the maximum correlation is determined. This corresponds to the point at which there is a maximum amount of overlap (i.e., the area the two beams have in common) between the two curves and is defined as the center of the received beam.

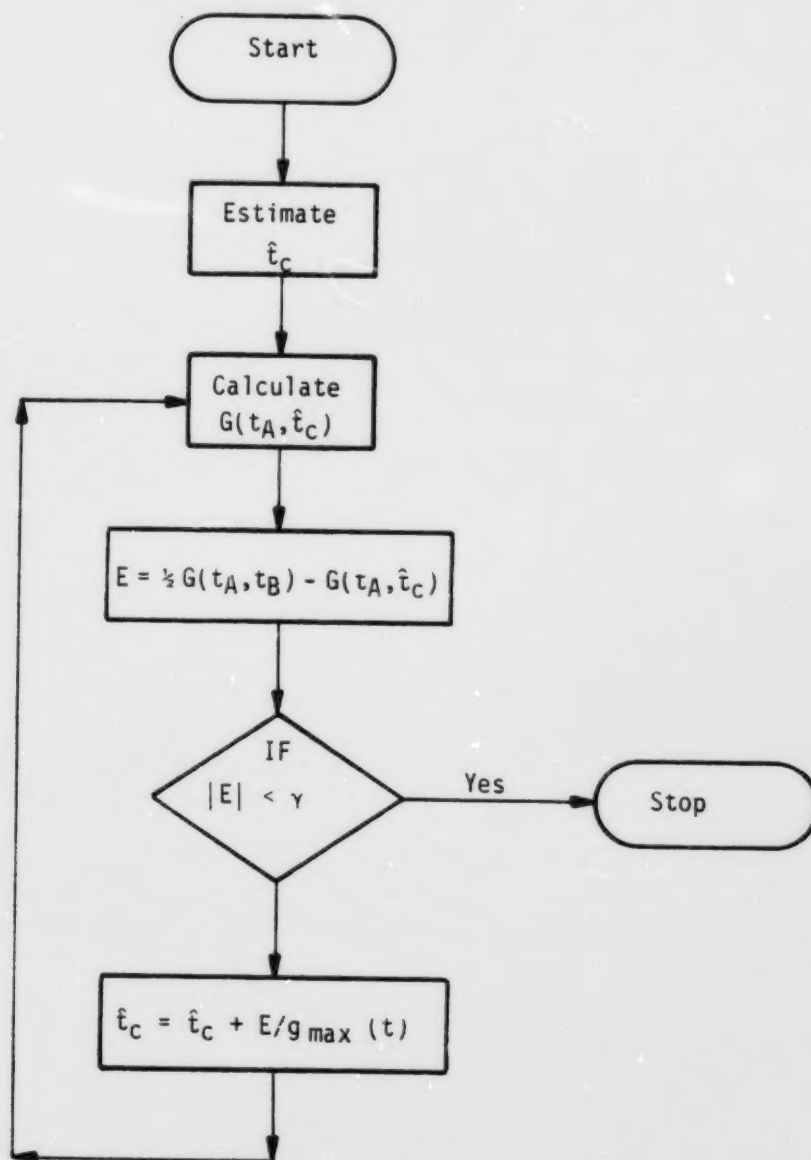


Figure 4.18 Iterative Process

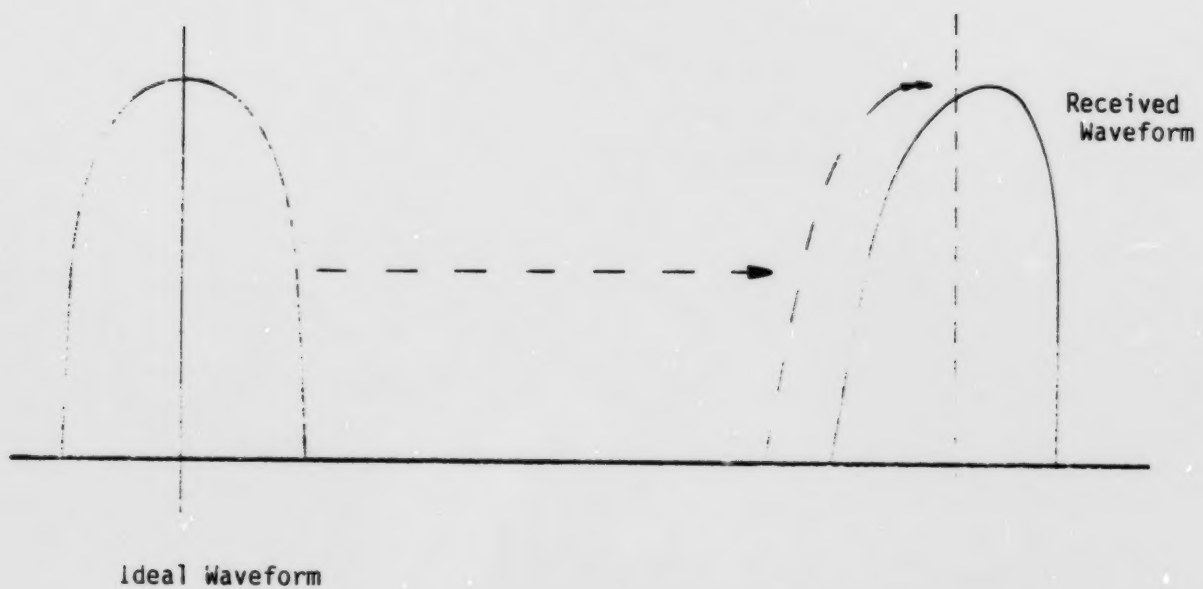


Figure 4.19 Correlation Method

The simplest criterion for determining the amount of overlap between the two curves is to simply correlate (i.e., multiply) corresponding samples of the ideal mainlobe with the received mainlobe. For simplicity, the ideal waveform could be normalized to the maximum amplitude of the received waveform.

The above algorithm could also be implemented using a different criteria for determining the beam center, that is, instead of determining the point of maximum overlap, one could minimize the error between the ideal waveform and the received waveform. The error criteria could be based on minimum absolute magnitude of error, signed magnitude of the error, or minimum mean square error. These criteria would all produce roughly equitable performance (the signed magnitude criteria would perhaps give the poorest performance, since errors would tend to cancel each other out), and would all suffer from the same potential drawbacks. Time scaling of the ideal beam width would be an issue of concern, since if the ideal beam was significantly wider or narrower than the received waveform, the resolving ability of the algorithm would be reduced. For example, there could be an interval of time during which the received waveform completely overlaps the ideal waveform, creating a region over which there is a constant maximum correlation. In such a case, one could not determine the beam center accurately.

The correlation technique would most likely require a software implementation. Since the algorithm involves a significant number of multiplications and additions, it could tend to be costly in terms of memory requirements and processing time requirements.

4.2.3.3 Least Mean Square Estimation of Beam Center

Another method of determining the guidance angle is to view each sample of the mainlobe as a random variable. Based on linear estimation theory (Ref.7), it is possible to predict the beam center using a linear combination of the mainlobe samples. Thus, the problem is to determine the optimal weighting of this linear combination for a given error criteria. Although there are several possible error criteria possible such as minimum mean square error, minimum variance or maximum likelihood, the minimum mean square error is preferred.

Referring to Figure 4.20, the received mainlobe is sampled at time instances t_i , the set (t_i) being determined by the occurrences of predefined amplitude thresholds with respect to the maximum beam amplitude. The set (t_i) is in fact a set of random variables, from which an estimate of the time of occurrence t_c , of the beam center is determined. Denote the estimate of t_c by $\hat{t}_c$. Using a linear estimation:

$$\hat{t}_c = a_0 + \sum_{i=1}^N a_i t_i \quad [1]$$

in which (a_i) is a set of weights for the set (t_i) . The term a_0 is a bias term. The mean square error ϵ of the above estimate is given by:

$$\epsilon^2 = (t_c - \hat{t}_c)^2 \quad [2]$$

$$= (t_c - a_0 - \sum_{i=1}^{N-1} a_i t_i)^2 \quad [3]$$

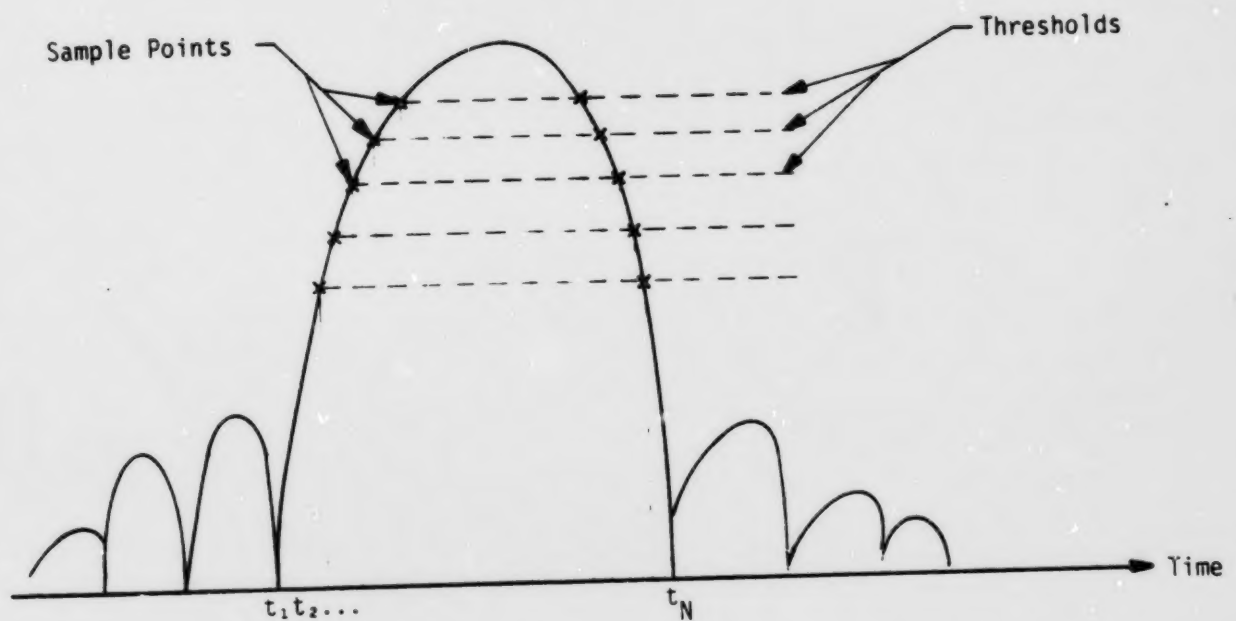


Figure 4.20 Weighted Prediction of Beam Center

In order to select the optimum weights, ϵ^2 must be minimized with respect to the weights (a_i). This leads to the well known orthogonality principle (the weights (a_i) that minimize ϵ are such that ϵ is orthogonal to (t_i)). The minimization is easily accomplished by differentiating [3] with respect to a_i and setting the result to zero. The result is the standard Wiener-Hopf matrix equation:

$$A = R_{t_i t_i}^{-1} R_{t_i t_i} \quad [4]$$

in which $A = [a_0 \ a_1 \ \dots \ a_{n-1}]^T$ is an $N \times 1$ matrix, $R_{t_i t_i}$ is an $N \times N$ correlation matrix given by

$$R_{t_i t_i} = \begin{bmatrix} E[t_0 t_0] & E[t_0 t_1] & \dots \\ E[t_1 t_0] & & \\ \vdots & & \\ E[t_{n-1} t_0] & \dots & E[t_{n-1} t_{n-1}] \end{bmatrix} \quad [5]$$

and $R_{t_i t_c}$ is an $N \times 1$ correlation matrix given by

$$R_{t_i t_c} = [E[t_0 t_c] \ \dots \ E[t_{n-1} t_c]]^T$$

In the above notation, $E[]$ denotes expected value and superscript "T" denotes the transpose of a matrix.

Once the optimal weights (in a mean square error sense) are obtained, an estimate of the beam center can be found by using equation [1]. The problem, therefore, reduces to one of determining the weights.

From equation [4], it can be seen that the weights are calculated from the $N \times N$ correlation matrix $R_{t_i t_i}$ (correlating elements in the set $\{t_i\}$), and the $N \times 1$ correlation of matrix $R_{t_i t_c}$, in which each element of $\{t_i\}$ is correlated with the actual time of occurrence of the beam center t_c . Calculation of the optimal weights depends on the nature of the "corruption" to the idealized beamshape. If the waveshape were not corrupted, i.e., were ideal, then the weights would be equi-distributed. For the case here, the corrupting signal is primarily due to sidelobe variations, either received directly from the antenna or via multipath.

One particularly suitable technique for establishing the weights in a non-ideal situation would be to conduct a "training-run", for the purpose of gathering statistical data on the beamshape as a function of spatial location. Intuitively, because the corrupting signals are at low levels, the sample points on the waveform at high signal levels will be assigned a higher weight, and those lower on the waveform will receive a lower weight.

The correlation matrices $R_{t_i t_i}$ and $R_{t_i t_c}$ will be obtained from a training run. This training run involves placing the test receiving unit at randomly selected spatial locations (see Figure 4.21) and measuring the set of random variables $\{t_i\}$ for a particular scan (both TO and FRO) as well as t_c . It should be noted that the matrices $R_{t_i t_i}$ and $R_{t_i t_c}$ are calculated from the statistics of the random process governing each random variable t_i . During the beamforming process, there are basically two types of errors that can occur, systematic errors (due to the state of the phase shifters), and random errors (due to Gaussian noise, multipath effects and random phase errors in the phase shifters).

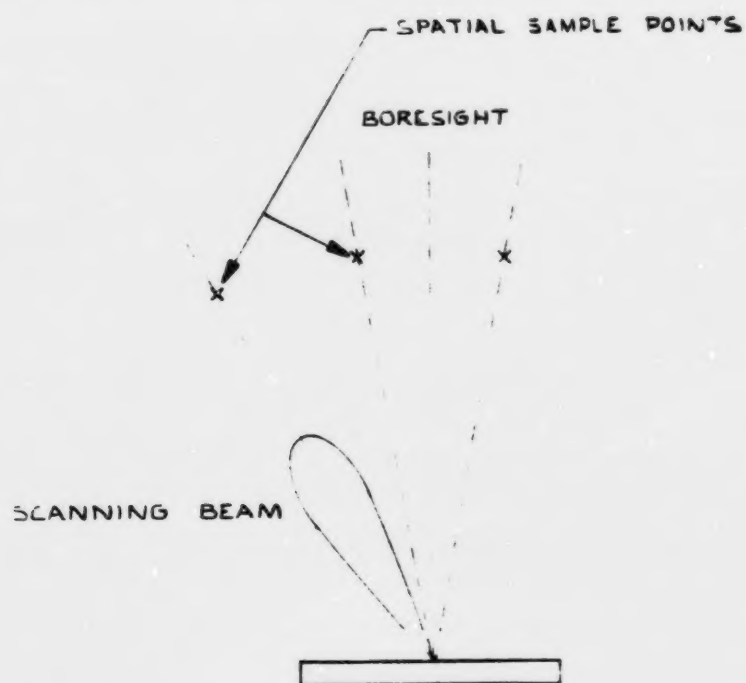


Figure 4.21 Training Run Implementation

It is assumed that in general the MLS antennas will use 4-bit phase shifters, resulting in 16 possible states. Thus in order to account for the systematic errors in the statistics of the ensemble of sets $\{t_i\}$, 16 scans (corresponding to the 16 states) would have to be obtained at each location. Furthermore to obtain statistical significance for the correlation of the random errors, one would require in the order of 256 to 512 sample sets $\{t_i\}$.

A set of suboptimal weights valid over the entire region of proportional coverage could be obtained by using an ensemble of sets $\{t_i\}$ gathered from several randomly selected spatial points in the region of proportional coverage. This would lead to a set of weights that are suboptimal for any given location, but optimal when averaged over the entire proportional coverage region.

The above discussion assumes that the amplitude levels at which the weights are determined are above a threshold, below which significant variation in the optimal weights would be observed at different spatial locations. This threshold level could be determined by performing a training run at commissioning.

The actual calculation of the weights by equation [4] involves the inversion of an $N \times N$ matrix and as such, the computational requirements increase on the order of N^2 as N increases. Furthermore, the memory requirements of storing all of the ensemble set $\{t_i\}$ increases linearly with N . For example, if 256 sample sets were used, one would need $2 \times 256 \times N$ bytes of memory, assuming each sample value was represented by one byte (the factor 2 arises since sample sets are required for both the TO and FRO scans). Studies have shown that typically the predictive gain due to increasing N , tends to saturate for values of N greater than 10. Thus for benchmark purposes, it will be assumed that $N=10$ (it is recommended that

the value of N at which the predictive gain saturates be determined experimentally during commissioning), with a resulting memory requirement of the order of 5K bytes.

The processing involved to calculate the weights (such as matrix inversion and calculating correlations) would only have to be performed once, (typically at commissioning) if the assumption is made that the weights do not vary with time (i.e., it is assumed that the random errors associated with beamforming are the result of a stationary random process). Thus, once the training runs have been performed, the actual processing needed to calculate the weights could be performed in non-real time. Having completed the training sequence and calculated the weights, the actual estimation of the beam center could be implemented as a transversal filter, as is illustrated in Figure 4.22. The transversal filter could be implemented in hardware using digital multipliers or alternatively, it could be implemented in software. Using a high speed floating point processor, one can perform 32 bit additions and multiplications in the order of 10-20 μ sec. Since each scan takes approximately 12.4 msec (for both TO and FRO scans), it is feasible that $\hat{r}_c$ could be calculated in real time. For example, for N=10, one would require time for 20 floating point operations, which could be achieved in less than 12.4 msec. However, time must also be allocated for A/D processing, memory read/write and processing overhead.

4.2.3.4 Measured Beam Center Considerations

It can be seen that the three proposed techniques for calculating the center of the beam only yield the ICAO defined beamcenter if the beam is symmetrical about the beamcenter centerline. As can be seen from Figure 4.11, the beam is not necessarily symmetrical about the centerline. Therefore, any algorithm which is used to calculate the centerline must include a correction factor which calculates the ICAO defined beamcenter from the calculated center of beam, a factor which, of course, depends on the measured beam asymmetry (skew).

4.2.3.5 Digitization and Sampling Considerations

Whenever digital algorithms are employed to process the angle information contained in the beam, the errors due to quantization, as well as any aliasing effects due to the sampling rate, must be considered.

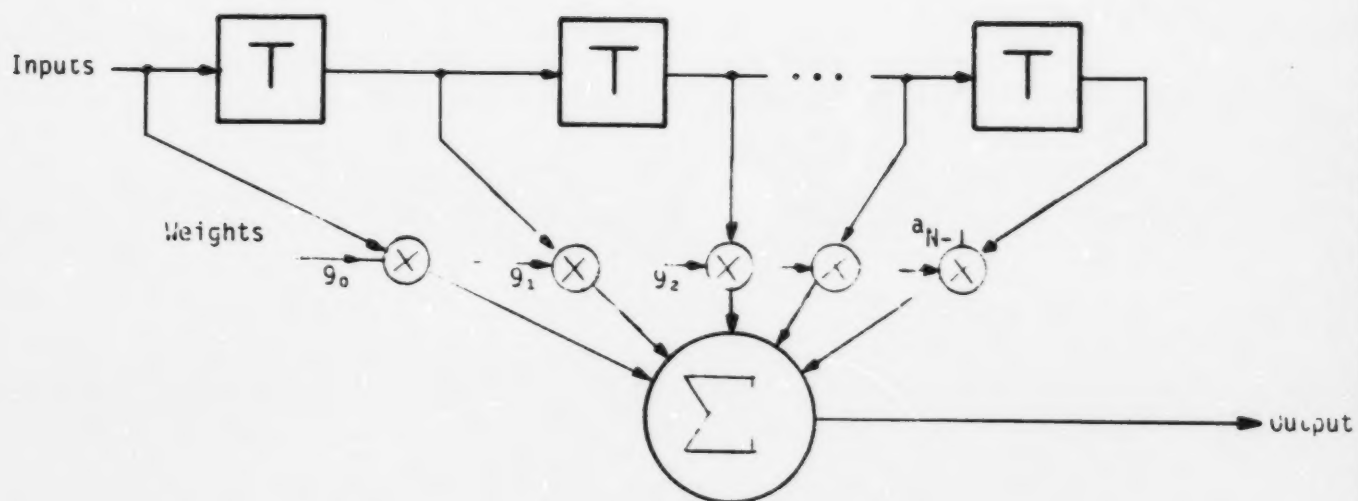


Figure 4.22 Transversal Filter Implementation of LMS Algorithm

a) Quantization Effects

The resolving ability of an A/D converter is determined both by the number of levels possible (2^M in which M is the number of bits in a binary A/D converter) and the manner in which the threshold levels are defined. Theoretically, any desired combination of threshold levels can be obtained using a companding characteristic in conjunction with a uniformly spaced A/D converter. The effect of the number of bits and possible threshold settings on the resolving ability of an A/D converter are examined below.

The waveform of Figure 4.23 is a typical analog waveform that could be received by an MLS receiver. Assume the peak of the waveform is normalized to unity (i.e., a value of 1.0 volts or 0 dB). Assuming an M bit quantizer with equally spaced thresholds (i.e., a constant voltage difference between each threshold). The thresholds would have voltage values of $\frac{1}{2^M}, \frac{2}{2^M}, \dots, \frac{2^{M-1}}{2^M}, 1$, giving a resolving ability of $\frac{1}{2^M}$ volts. However when expressed in decibels, the resolving ability R_x becomes:

$$-20 \log \frac{n-1}{n} \leq R_x \text{ (dB)} \leq -20 \log_{10} \frac{n}{n+1}$$

in which $10^{x/20}$ (x is the level in decibels) is a voltage level between thresholds n-1 and n, where $n=1, 2, \dots, 2^M$ is the threshold number corresponding to the voltage level $\frac{n}{2^M}$. The total dynamic range of an M bit quantizer, for the above configuration, can easily be seen to be $20 \times M (\log_{10} 2)$ dB (i.e., from 0 dB to $20 \log \frac{1}{2^M}$ dB).



Figure 4.23 Threshold Quantization

A second method of setting the threshold levels is to space the threshold levels equally in terms of decibels, rather than in terms of voltage. Since there are 2^M possible levels and the dynamic range is $20 \times M \times \log 2$, it follows that for an M bit quantizer, with thresholds equally spaced in terms of decibels, that the resolving ability is given by:

$$20 M \log_{10} 2 / 2^M \text{ dB}$$

The corresponding voltage levels are given by the expression

$$V = 10 \left[\frac{n \log_{10} \frac{1}{2^M}}{2^M} \right] \quad n=0, 1, \dots, 2^M-1$$

It should be noted that thresholds equally spaced in decibels can easily be obtained by using a logarithmic amplifier and sampling the output voltage with a linear quantizer.

Based on the above discussion, the resolving abilities of a quantizer equally spaced in voltage, or in decibels, is shown in Table 4.10 for various numbers of bits M. It can be seen that the resolving ability of an A/D with thresholds of equal voltage spacings is superior to that of an A/D with thresholds with equal decibel spacing, in the range of interest for angle processing. As the sample level decreases, the resolving ability of the equally voltage spaced thresholds decreases, until it reaches a point at which it is poorer than the thresholds with equal decibel spacings.

Table 4.10¹¹

	Equal Decibel Spacings Resolving Power (dB)	Equal Voltage Spacings Resolving Power (dB)
8 bits	0.19	-3 dB: 0.05 -6 dB: 0.07 -9 dB: 0.10
12 bits	0.018	-3 dB: 0.003 -6 dB: 0.004 -9 dB: 0.006
16 bits	0.0015	-3 dB: 0.0002 -6 dB: 0.0003 -9 dB: 0.0004

From computer simulation of a Taylor beam pattern, it was found that for a beamwidth of 2° , the slope at the -3 dB point was approximately 6.7 dB/degree, whereas at the -10 dB point, the slope was 13.7 dB/degree. Assuming that the angular error contribution due to the A/D converter is required to be less than 0.005° , one would require a resolving ability of 0.03 dB at the -3 dB point and 0.07 dB at the -10 dB point. Comparing this requirement to Table 4.10, one can see that a 12 bit quantizer is required. An alternate implementation would be to use an 8-bit quantizer with a companding characteristic that compresses the threshold levels near the maximum of the beam, resulting in a higher resolution at the required sampling points (at the expense of the resolving power at the noisy lower power levels).

b) Sampling Rate Effects

Errors due to aliasing can result if sampling rate is improperly chosen. The beam envelope is to be filtered by a 2-pole lowpass filter with a 3 dB cutoff of 26 kHz. For a 2-pole filter, the attenuation is 12 dB/octave. If the sampling rate is f_S Hz, then the maximum frequency $f_{\max}$ of the signal that will not be aliased is $1/2 f_S$. Such a frequency would be $\log_{10} \left[\frac{f_S \text{ (kHz)}}{52} \right] / \log_{10} 2$ octaves above 26 kHz. Therefore, its effect would be attenuated by:

$$12 \cdot \log_{10} \left[\frac{f_S \text{ (kHz)}}{52} \right] / \log_{10} 2 \text{ dB}$$

For example, if $f_S = 1$ MHz, it is found that $f_{\max}$ is attenuated by -51.2 dB (equivalent to an error of 0.04 dB at the -3 dB point - i.e., by converting -51.2 dB to volts and comparing to -3 dB).

Another factor that affects the minimum possible sampling rate is the maximum slope of certain waveforms. For example, the rise time of a DPSK pulse must be less than 10 μ sec. This would require a sampling rate of 1 MHz in order to obtain 10 samples within the 10 μ sec (from which one could obtain a reasonably accurate measurement of the rise time). Similarly, when sampling the main lobe for angle processing, 20 to 100 samples may be required (depending on the algorithm employed). For a typical beamwidth of 2° (100 μ s), this translates into a sampling rate of 200 kHz to 1 MHz.

4.2.4 MULTIPATH MEASUREMENTS

As indicated previously, multipath, that is, signals arriving at a point following multiple paths, introduces a significant problem for measurement of MLS performance. This is because the reflectors which serve as the source of the multiple path signals can cause multipath signals which vary dramatically in magnitude at different points in the coverage volume. Therefore, measurements made at a specific point in the coverage volume, for example, close to the MLS, cannot be used to predict performance elsewhere in the coverage zone.

This causes two problems. The first is that multipath causes errors to be made in measurement of quasi-near field parameters. This problem and possible solutions were described in Section 4.2.2.

The second problem is that ICAO requires that measurement of system guidance accuracy be made over the entire coverage volume; these measurements to include propagation effects (which are predominantly multipath). Unfortunately, ground based measurements are therefore not meaningful and airborne testing must be performed.

However, it is possible to reduce the amount of airborne testing by conducting some ground based tests, in particular, sidelobe tests. To explain the reasoning behind this statement, it is necessary to briefly explore the characteristics of MLS multipath signals. Multipath, as related to MLS, is discussed in great detail in Ref. 11 (MLS Multipath Control Techniques, R.J. Kelly), which, for the sake of brevity, is not reproduced in this report. However, antenna sidelobes are seen to be the major source of multipath error, assuming direct beam reflections (where the reflector is located within 1.7 beamwidths of the main beam) on final approach can be avoided by conforming to standard runway obstacle clearance regulations.

With the AZ system, azimuth pattern sidelobes can cause lateral multipath, for example, signals reflected off buildings (see Figure 24a). With the EL system, elevation pattern sidelobes will cause ground reflected multipath as shown in Figure 4.24b.

Figure 4.24c illustrates the effect of ground reflected sidelobes in the non-scan plane of the AZ system. These sidelobes are of lesser significance because while they cause amplitude errors, guidance errors are not caused unless there is some assymetry in the reflecting surface.

Figures 4.25a and 4.25b illustrate the effect of ground reflected multipath as approach angle decreases as measured in early flight trials on MLS. It can be seen clearly that for the Elevation system, as the approach angle is reduced from 7° to $2\frac{1}{4}^\circ$, that PFE and CMN increase significantly due to ground reflected multipath, whereas for the AZ system, the change is insignificant.

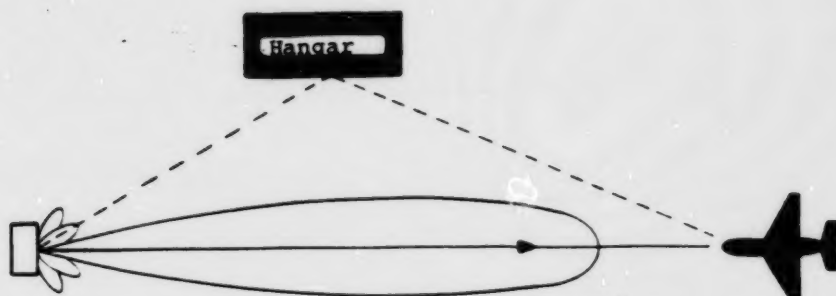


Figure 4.24a Multipath Caused by Scan Plane Sidelobes (AZ System)

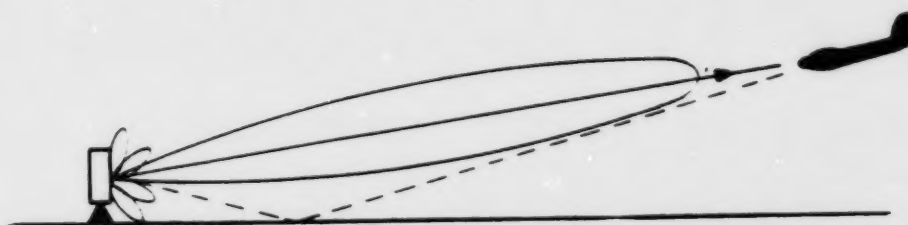


Figure 4.24b Multipath Caused by Scan Plane Sidelobes (EL System)



Figure 4.24c Multipath Caused by Non-Scan Plane Sidelobes (AZ System)

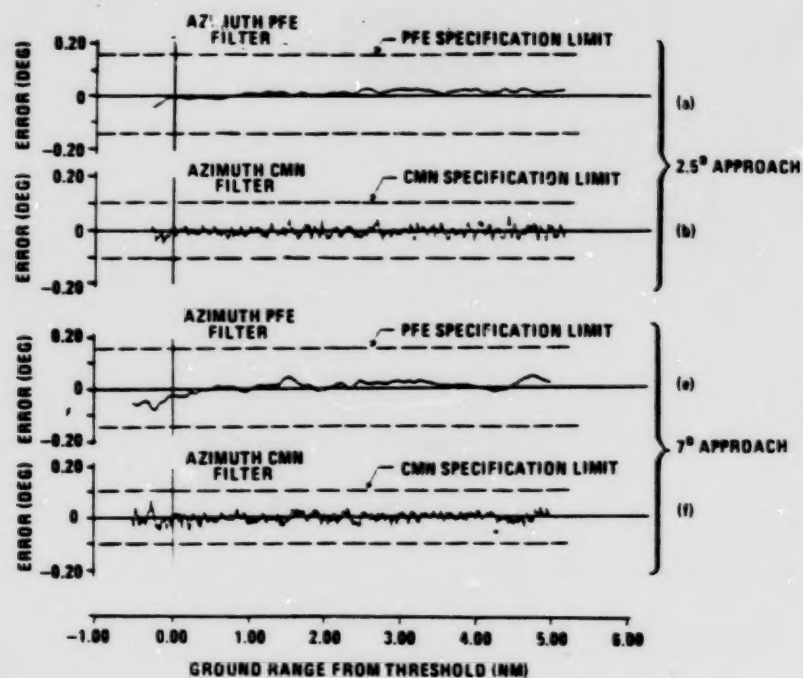


FIG. 4 Bendix SMCS flight tests (NAFEC, New Jersey).

Figure 4.25a Azimuth PFE/CMN Variation with Approach Angle

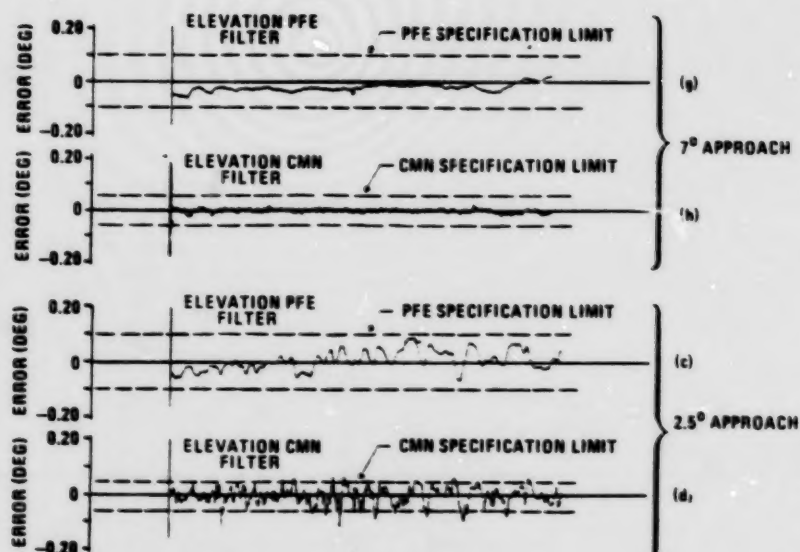


Figure 25b Elevation PFE/CMN Variation with Approach Angle

4.2.4.1 Sidelobe Levels Analysis

The ICAO SARP recommends that the dynamic sidelobe levels:

- i) Be compatible with guidance error limits
- ii) Not persist at a level less than 10 dB down from the main lobe.

The required sidelobe level compatible with guidance error limits can be calculated from ICAO specifications based on "typical" airport reflector characteristics. A sample calculation for the approach reference point is provided on the basis of the following presumptions.

- i) SNR greater than 20 dB
- ii) High data rate azimuth system
- iii) 2° beamwidth AZ antenna, 40° lateral coverage
- iv) 1½° beamwidth EL antenna, 20° elevation coverage
- v) AZ located 11,000 ft from datum, and EL located 950 ft from datum.

a) Propagation Error Analysis

From the data contained in Tables 3-12 to 3-15, the CMN limits for each portion of the AZ system can be allocated as follows:

- a) Entire system, CMN $\leq \pm 0.043^\circ$
- b) Airborne receiver, CMN $\leq \pm 0.015^\circ$
- c) Ground equipment, CMN $\leq \pm 0.017^\circ$, excluding multipath

Therefore, propagation errors (primarily multipath) can be calculated using the root sum of squares (rss) technique because all of the errors are statistically independent.

$$\text{Multipath} = \sqrt{(.043)^2 - (.015)^2 - (.017)^2} = \pm 0.037^\circ$$

Table 4-11 tabulates the calculated multipath portion of the guidance angle error limits for PFE and CMN.

Table 4-12 Multipath Error Component

		Accuracy ($\pm$ degrees)	
		AZ	EL
CMN	System	.043	.059
	Ground (TX)	.017	.030
	Air (RX)	.015	.010
	Multipath (calc.)	.037	.050
PFE	System	.081	.120
	Ground (TX)	.051	.060
	Air (RX)	.017	.017
	Multipath (calc.)	.061	.103

Having calculated the multipath error component, the allowable dynamic sidelobe level can be calculated for the ground equipment using the ICAO defined equation:

$$\text{PESL} \cdot \text{PR} = \frac{d\theta}{\theta_{\text{BW}} \cdot \text{PMA}}$$

where:

- PESL = effective sidelobe level
- PR = Multipath obstacle reflection coefficient
- θ_{BW} = antenna beamwidth
- PMA = Motion averaging factor
- $d\theta$ = angular error
- and $(\text{PMA})^2 = \frac{2 \times (\text{output filter noise bw})}{\text{function data rate}}$

For the azimuth function, the output CMN filter bandwidth is 1.6 Hz, corresponding to an equivalent noise bandwidth of 2.4 Hz.

PMA is equal to one for the Elevation function because the scalloping frequency is generally below 1.6 Hz for ground reflected multipath, which is the major source of multipath signals.

Table 4-13a tabulates the value of $\text{PESL} \cdot \text{PR}$ for typical AZ and EL functions beamwidth of 2 and 1.5 degrees respectively, based on the CMN limits.

PESL is also tabulated for a typical value of -6 dB for PR.

Table 4-13a Required Effective Sidelobe Levels (CMN Limits)

	$d\theta$	P_{MA}	$20 \log (PESL \cdot P_R)$	P_R (assumed)	$20 \log PESL$
Azimuth ($2^\circ BW$); H.R.	0.037	0.351	-25.2 dB	-6 dB	-19.2 dB
L.R.	0.037	0.608	-30.0 dB	-6 dB	-24.0 dB
Elevation ($1\frac{1}{2}^\circ BW$)	0.050	1.0	-29.7 dB	-6 dB	-23.7 dB

NOTE: H.R. = high rate; L.R. = Low Rate

b) FAA Sidelobe Limits

It is also interesting to examine the FAA proposed limits on sidelobe suppression as stated in FAA-E-2721/2 (Ref. 9). Table 4-13a tabulates the FAA required values, showing that maximum AZ antenna sidelobe levels of -19.4 dB and EL antenna sidelobe levels of -24.1 dB below the main beam are required. These values are similar to those derived above based on a guidance error analysis (for the same scan rate).

Table 4-13b FAA ESL Requirements

	$d\theta$	P_{MA}	$20 \log PESL \cdot P_R$	P_R (dB)	PESL
Azimuth (2°)	0.065	.62*	-25.4 dB	-6 dB	-19.4 dB
	(CMN)				
Elevation (1.5°)	0.083	1.0	-25.1 dB	-1 dB	-24.1 dB
	(PFE)				

*Based on low-rate approach azimuth

c) Sidelobe Level Requirements

These results clearly show that sidelobe level limits for the MLS should be related to the expected reflection factors at any given airport. This can be seen more clearly by examining Figures 4.26 and 4.27 which graphically plot the required sidelobe level performance against reflection factors. (In accordance with References 10 and 11, a correction factor of $\sqrt{2}$ has been applied to the equation to account for the fact that the multipath effects on the leading and tracking edges are independent. This reduces the sidelobe requirements by 3dB.)

The FAA defined limits plotted on the same graphs show agreement within 1½dB of the equation.

The requirement for sidelobe limits must then be related to the expected reflection factor at any given airport. Reflection factors were measured by Lincoln Labs (Ref 8) in 1978/79.

i) Azimuth System Test Results

A multipath measurement program was undertaken at four U.S. airports whose geometry suggested the possibility of substantial multipath, i.e., St. Louis, Miami, Tulsa and Wright-Patterson AFB. The results of these tests are tabulated in Table 4.14.

It can be seen that a high rate MLS AZ with a sidelobe level of -13dB (based on the ICAO equation) would be ample for St. Louis with a reflection factor of -9dB peak. However, for Tulsa, a sidelobe level of -25 to -30dB would be needed.

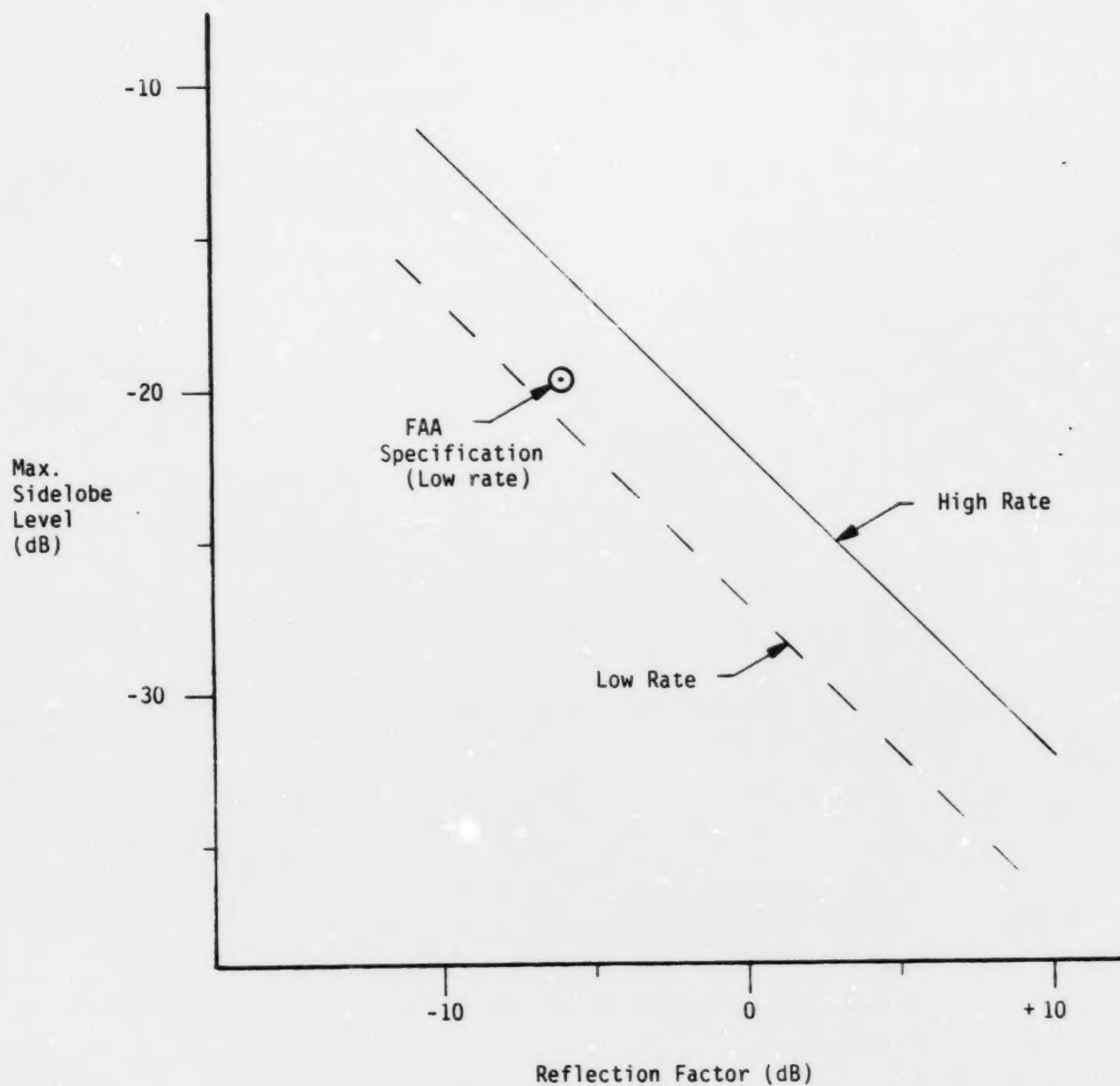


Figure 4.26 Sidelobe Level for Azimuth System

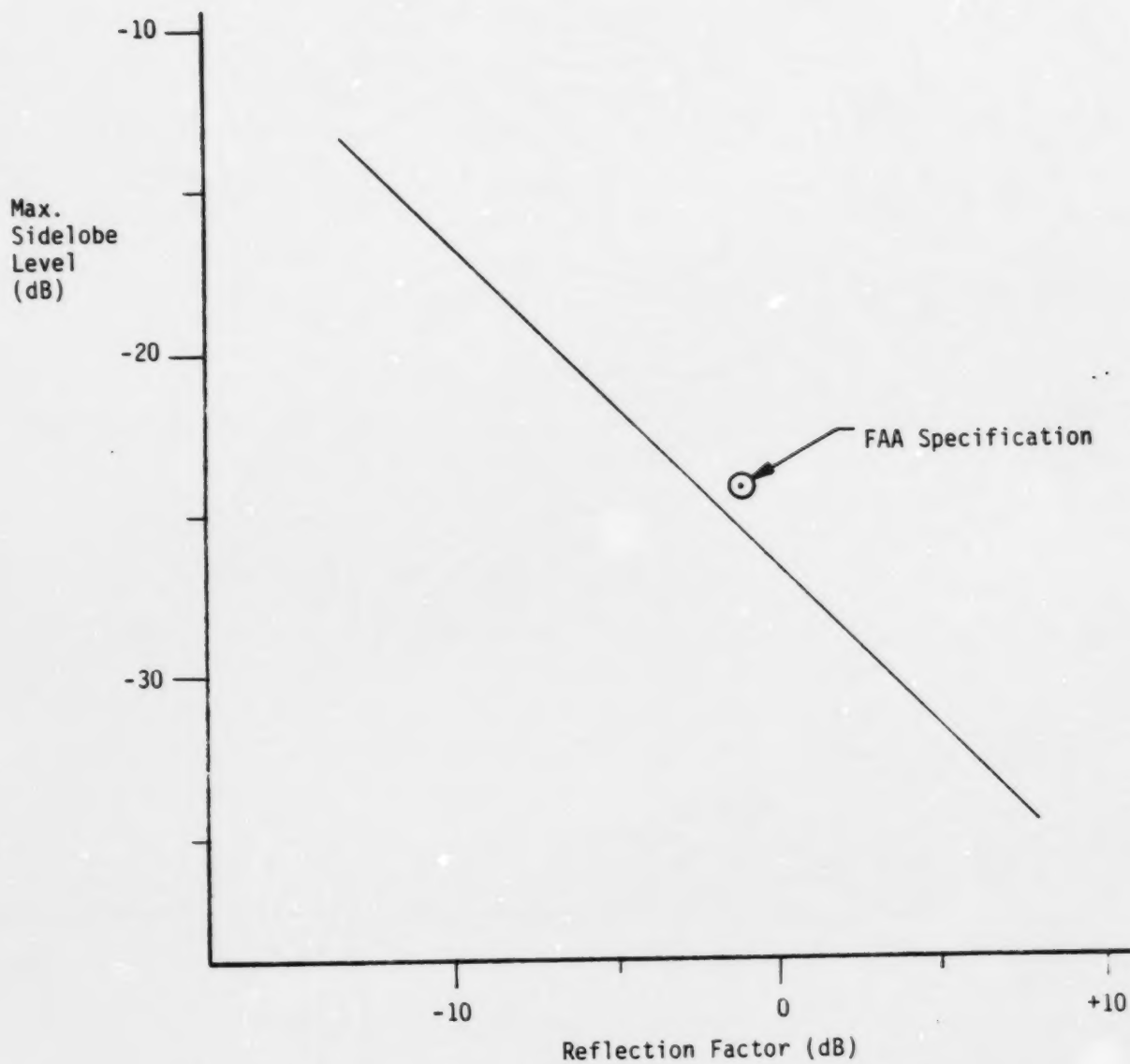


Figure 4.27 Sidelobe Level for Elevation System

Table 4.14

Airport	Peak Multipath Levels (dB Relative to Direct	Scalloping Frequencies* (in Hz)	Multipath Duration+ (Secs)	Location
St. Louis International	-9 -9	700 800	2 5	Threshold Flare
Tulsa International	+3 to +8	50 800	7 0.3 to 1.0	Threshold Flare
Wright-Patterson Air Force Base	0 -1	400 270	2 1	Flare Threshold
Miami International	+3	75	4	Orbital Flights at 6 nmi

+ Period that multipath remained within 6dB of its peak level.

* At approximately 120 knots on final approach and 150 knots on orbital flights.

ii) Elevation System Test Results

Ground reflection tests were undertaken at Hanscom AFB and at Ft. Devens golf course in the U.S. The results are shown in graphical form in Figure 4.28, plotting peak values of reflection factor against estimated reflection angle. Reflection factors between -1 and -3dB were most common. (The measurements were taken on fairly flat terrain at Hanscom AFB and more rolling ground on the golf course.) The measurements were taken at L band rather than C band, a 5:1 ratio in frequency. Therefore, the results may be somewhat in error, although because the surface is very rough, it is unlikely the error would be very large. At higher frequencies, the surface roughness is effectively increased due to the shorter wavelength.

Again using the ICAO equation, a sidelobe level (on the groundward side of the main beam) requirement of -26dB is calculated based on a -1dB reflection factor.

4.2.4.2 Multipath Prediction

It can be seen that, particularly for the AZ MLS, the minimum acceptable antenna sidelobe level can vary from one airport to another depending on the presence or absence of multipath sources such as buildings.

It is therefore proposed that sidelobe level be measured at a First Article Test Facility, and then, with the aid of airport site photographs and maps, the areas of anticipated worst case multipath could be predicted. This approach could serve to significantly reduce the amount of flight time and therefore, reduce commissioning costs.

It is important to realize that the ICAO sidelobe level equation assumes all airborne receiving equipment will respond in an identical fashion to in-beam multipath. For the purposes of this study, this has been assumed to be true. The FAA sidelobe tests defined in FAA-E-2721/2 utilize a MLS receiver as part of the test, presumably in an effort to include the

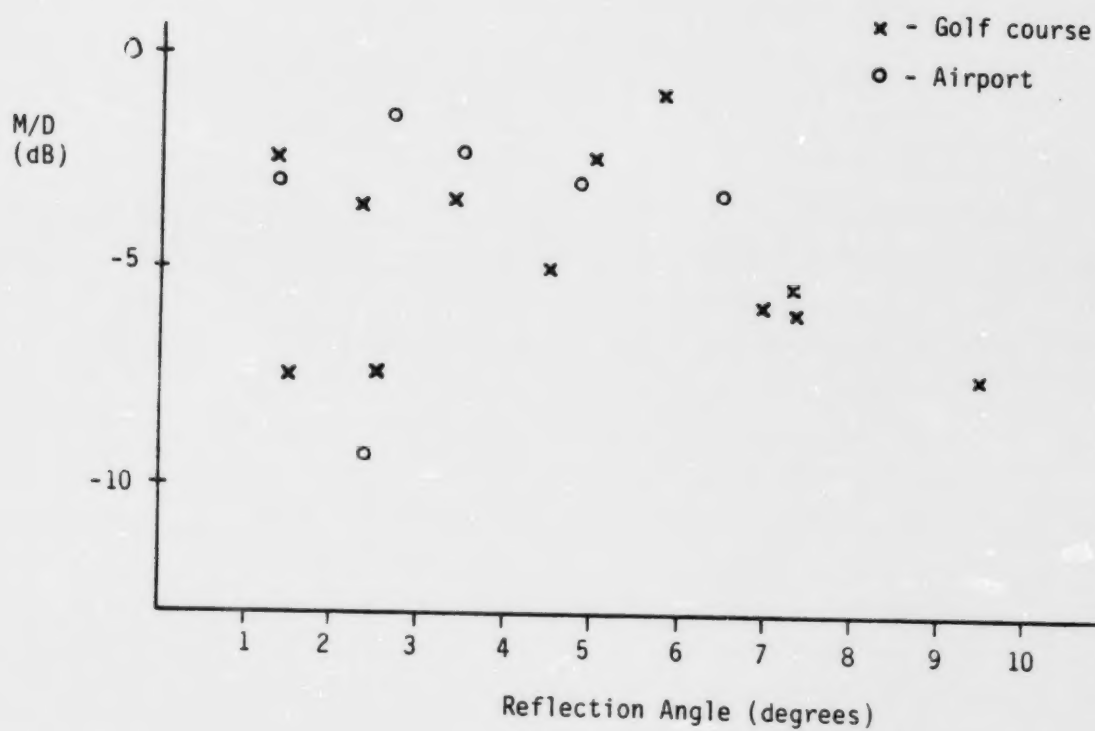


Figure 4.28 Ground Reflection Measurements

receiver effect. It is not obvious such an approach has any advantage and it is considered beyond the scope of this study to consider this possibility.

4.2.4.3 Effective Sidelobes

The term effective sidelobes has been coined by ICAO to refer to the effect of:

- i) Directive Antenna Pattern
 - ii) Randomness of the Sidelobes
-
- a) Directivity

The directivity of the antenna patterns can significantly effect the performance of the MLS system when the reflectors are located outside of the coverage volume. While ICAO does not require the antenna pattern to be controlled outside of the coverage volume, the SARP does recommend that:

- The horizontal radiation pattern of the Elevation Antenna should be reduced by 3dB at 20° off boresight and by 6dB at 40° off boresight.

Although the SARP does not make a similar recommendation for the Azimuth Antenna, the FAA does. FAA E-2721/2 requires that, for the AZ Antenna, the radiation pattern be controlled as follows:

- At elevation angles below the peak, the vertical radiation pattern shall exhibit a slope of -8dB per degree at 6dB below the peak and at angles below the first null, the pattern lobes shall be at least 14dB down.

It is recommended that Transport Canada adopt these two requirements as firm requirements for MLS systems in order to reduce the possible ground effect for the EL Antenna and to reduce the potential effect of out-of-coverage reflectors such as buildings for the AZ Antenna.

b) Randomness Effect

The aircraft moves through an interference field caused by diffuse reflection from a rough surface, the interference pattern will be random in time (i.e., noise-like). Although both the leading and trailing edges of the beam pattern will be affected equally the effects will not generally be correlated if the multipath is random. Therefore, the beam errors have been reduced by a factor of $\sqrt{2}$ based on this presumption.

4.3 ENVIRONMENTAL SENSITIVITY OF MLS ANTENNA

The major benefit of a commissioning test system is that a MLS can be certified and into service in a reasonably short time. However, these tests assume the system will behave identically under all variations in weather conditions; otherwise, the commissioning tests would have to be spread over four seasons. The purpose of this section of the report is to examine these environmental effects, determine which effects are likely to be troublesome and then propose test techniques.

For the purposes of this study, it has been assumed that factory tests have been performed on the MLS electronic circuits over a wide variation in temperature, humidity, etc. and therefore, it is assumed that the electronics are essentially unaffected by environmental conditions. The area of concern that may be difficult to factory test is the radiation characteristics of the antenna under differing environmental conditions.

Due to the proprietary nature of MLS antenna designs and the large number of alternative design concepts (i.e., slot radiators, dipole radiators, microstrip patch radiators, etc.) that may be used in a scanning beam array antenna, the analysis is qualitative rather than quantitative for the most part. To avoid the necessity of having detailed knowledge of the mechanical construction of the antenna, it will be assumed that the individual antenna elements will be unaffected by environment, and that the environmental affects will be only on the array as a whole. This approach simplifies the modelling considerably and is not unrealistic since the individual elements each only contribute a small amount to the overall array performance.

As seen by the analysis in the previous sections, the angle guidance accuracy requirement is the most severe requirement for the MLS, and therefore, the analysis will concentrate on environmental effects on angle guidance accuracy.

The following environmental conditions and their effect on antenna performance will be considered:

- i) Temperature - Variation in temperature can cause the array size to vary due to thermal expansion or contraction thereby changing the scan angle of the radiation pattern.
- ii) Humidity - The effects of variations in humidity can be assumed to be negligible for metallic antennas unless water (due to condensation) collects on or in radiating elements or connections. Dielectric elements (i.e., microstrip or dielectric lens), however, may be affected more severely.
- iii) Rain and Ice - It is assumed the antenna is totally enclosed in an enclosure with a radome "window" on the front, therefore, rain cannot reach the antenna elements. However, rain which collects on the surface of a "radiation transparent" radome can have a significant effect. Should this rain turn to ice and then collect on the surface, performance would also be degraded.
- iv) Sand and Dust - It is assumed the antenna is enclosed in a sealed enclosure; therefore, sand or dust should not be able to enter. In any case, unless the antenna has moving parts such as a motor, sand and dust should not cause performance degradation.
- v) Vibration - Wind induced vibration could be a problem because of the exceedingly tight tolerance on beam pointing accuracy.
- vi) Corrosion - The antenna and radome array may corrode, particularly due to salt fog or acid rain. Consideration of this effect is considered beyond the scope of this study.

4.3.1 TEMPERATURE SENSITIVITY

Temperature may affect the accuracy of the antenna array by causing the array to change shape mechanically by expanding or contracting. Depending on the materials used to construct the antenna array, the mechanical perturbation of the array could involve motion of the individual array elements in any of three planes, producing changes in the direction or shape of the scanning beam or the sidelobe structure. Ultimately, errors caused by these perturbations can best be determined by measurement of MLS performance.

In order to estimate the magnitude of the potential problem, a computer simulation was prepared using a simplified model of the mechanical expansion of the antenna array. For the sake of simplicity, it was assumed that the expansion or contraction between all array elements was uniform (i.e., the temperature distribution was uniform) and that the expansion or contraction only occurred along an axis containing all the array elements (i.e., there was no motion perpendicular to that axis) as modelled in Figure 4.29. While this model is overly simplistic, it will serve to indicate if there is a problem, since it could actually occur.

A Taylor distribution was used to model the antenna array based on a sidelobe level of -30 dB with respect to the maximum of the mainlobe, and assuming the number of constant sidelobes to be $\bar{n} = 4$. The array was also assumed to have an interelement spacing of $\lambda/2$. ($\lambda = 5.93$ cm. for an RF frequency of 5.06 GHz). The total number of elements in the array was assumed to be 64, representing an antenna with a physical aperture of approximately 1.87 meters.

It is known from antenna theory (Ref. 13) that the array factor of an N-element linear array is given by the expression (in the far field).

$$A(\phi) = \sum_{n=0}^{N-1} i_n \exp [jn\beta D \sin \phi]$$

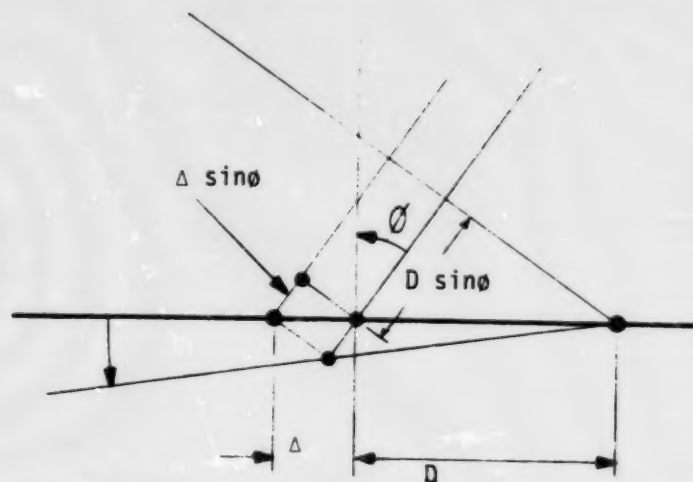


Figure 4.29 Array Model

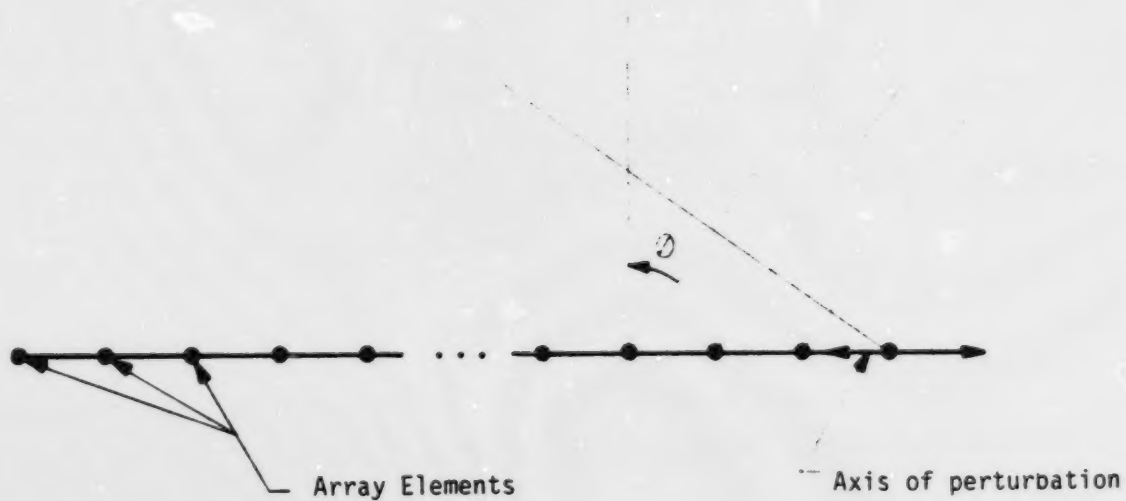


Figure 4.30 Perturbation Model

in which ϕ is the angle between boresight and the scan angle (see Figures 4.30), $\beta = 2\pi/\lambda$ is the wave number, D is the interelement spacing and i_n is the complex current flowing in the n^{th} element of the array. Other simplifying assumptions used in the analysis were that the current distribution was assumed to be uniform, that the element patterns were assumed to be isotropic, and that perfect phase shifters were included.

Referring to Figure 4.30, it can be seen that for a scan angle ϕ , a perturbation of Δ will produce a phase error in the n^{th} element of $n\Delta \sin\phi$. In fact, such an error is equivalent to an antenna misalignment angle of:

$$\sin^{-1} \left(\frac{\sin 2\phi}{2\sqrt{\Delta \sin^2 \phi (\Delta + 2D) + D^2}} \right)$$

Thus, the angle guidance error increases with increased scan angle. Assuming an aluminum mounting for the antenna array elements with a temperature coefficient of $12.4 \times 10^{-6}/^\circ\text{C}$, the change in interelement spacing Δ would be 0.14% for a change in temperature from -55°C to $+55^\circ\text{C}$.

Using $\Delta = -0.001$ and a scan angle of 60° (near the upper limit of the antenna scan) and substituting the phase error in the array model, it was found that the center of the mainlobe was in error by 0.1° by searching for the maximum of the beam. A similar error was obtained if the beam center was determined instead of the midpoint between the two 3 dB points. The results are tabulated in Table 4.15. It is interesting to note that by using the 3 dB points of the theoretical beam (i.e., perfect) to determine the beam center, the calculated beam center is in error by $+0.062^\circ$. This "skew" is due to the fact that the beam is "spread" at progressively greater approach angles by an amount equal to $1/\cos \theta$ (essentially because the array size as seen by the viewer is reducing as the angle increases). The resulting variable rate of beam spreading causes the beam to skew.

Comparing the potential errors to the ground equipment accuracy limits of Table 3.19, it can be seen that the effects of temperature expansion and contraction are indeed a potential problem (i.e., the allowed PFE is 0.05° for an azimuth antenna on a typical runway). Thus, it is recommended that these effects be measured in order to determine if the manufacturer has properly compensated for thermal expansion/contraction.

Table 4.15

Offset	-0.001	0.001	0.0
Scan Angle [Deg]	60.0	60.0	60.0
Angle at Beam Maximum [Deg]	60.1	59.9	60.0
Error [Deg]	+0.1	-0.1	0°
1st 3 dB Point [Deg]	58.129	57.945	58.037
2nd 3 dB Point [Deg]	62.196	61.981	62.087
Midpoint of 3 dB Point [Deg]	60.163	59.963	60.062
Error [Deg]	+0.163	-0.037	+0.062
Relative Error [Deg]	+0.101	-0.099	0

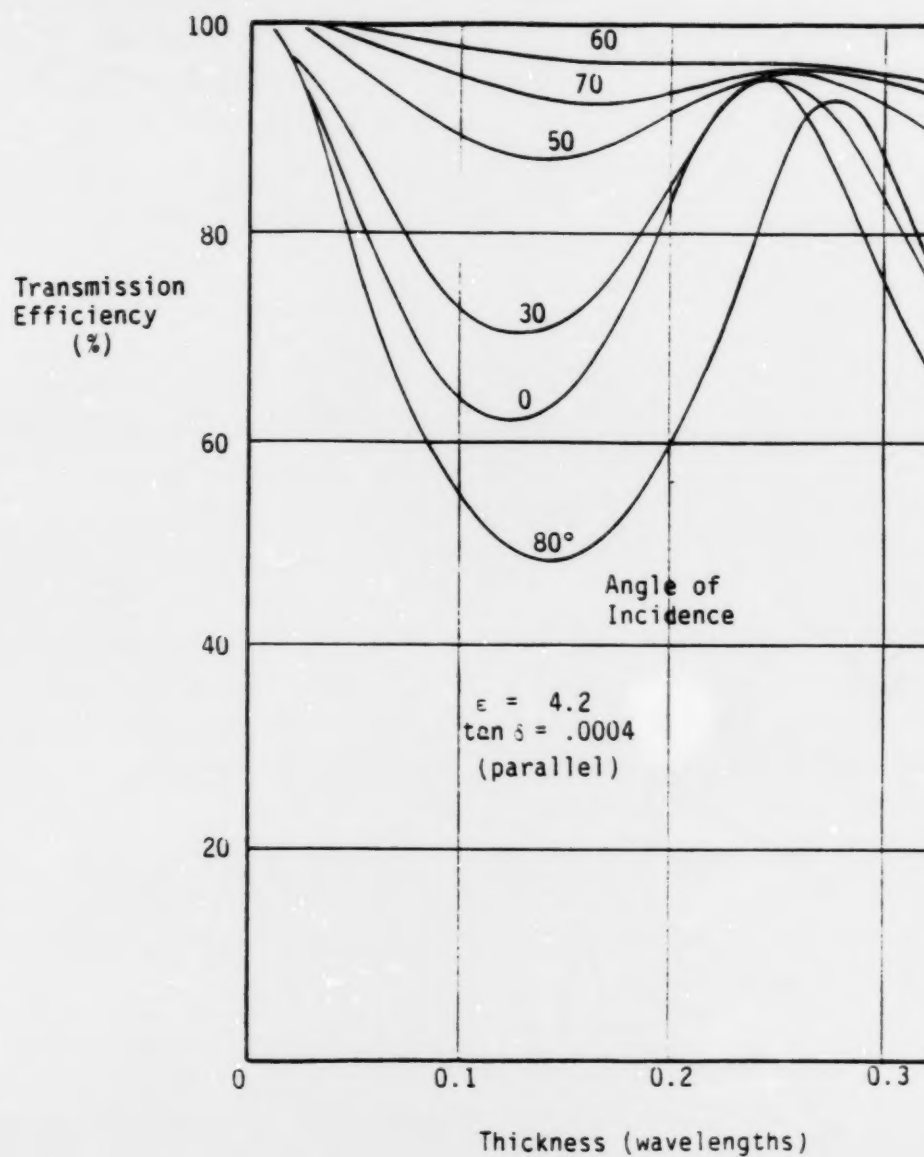
4.3.2 HUMIDITY SENSITIVITY

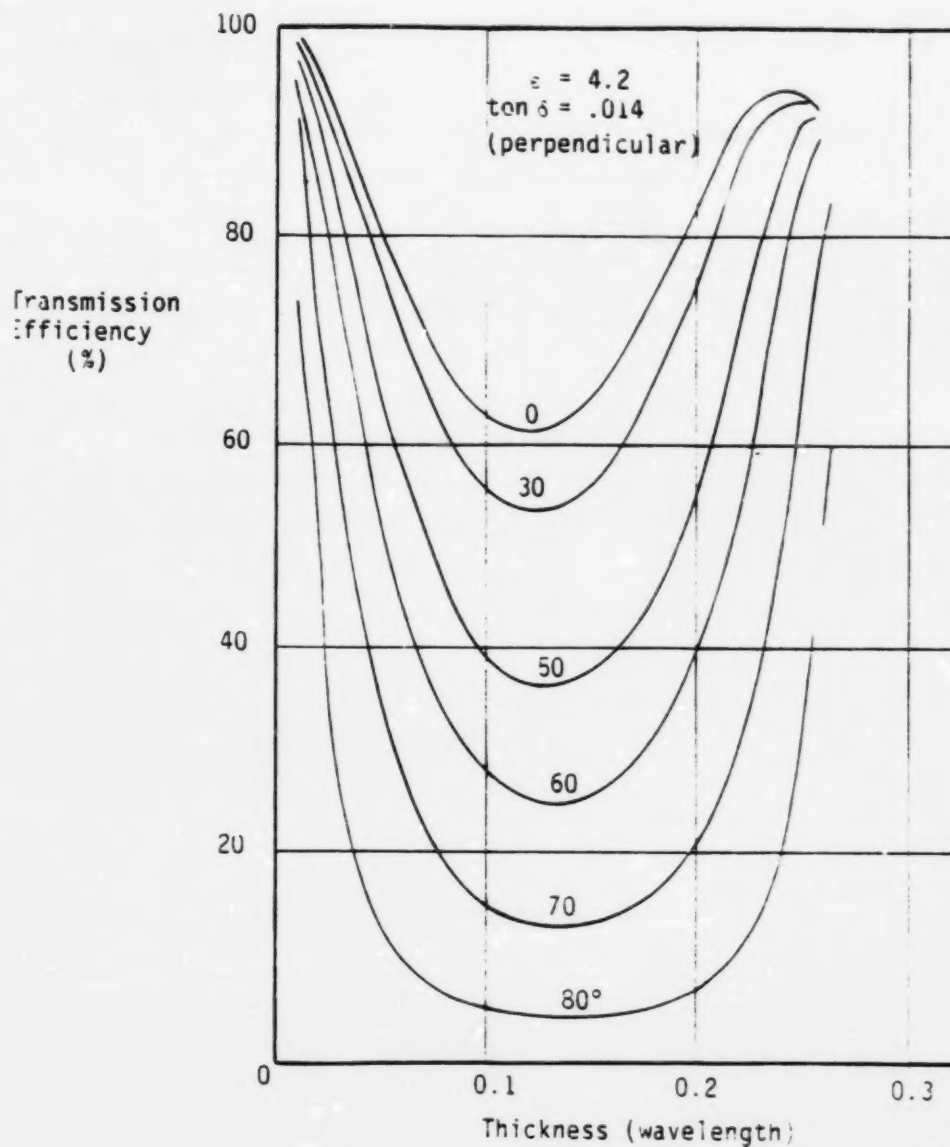
Under conditions of high humidity, condensation can cause water to form on surfaces, particularly if the temperature should drop quickly. This might cause problems if the water collects in radiating elements or on coaxial connections. The effects, in general, are not predictable in advance except possibly after a close inspection of a particular design. Antennas which utilize dielectrics in their construction, such as microstrip radiators or lens type antennas, may be even more susceptible to degradation caused by moisture if particular care is not used to prevent moisture from collecting close to the surface of the dielectric.

4.3.3 RAIN AND ICE

The MLS radome will almost certainly be designed as a thin skin radome. The performance at 5 GHz may be presumed to be equivalent to that of a radome with a 3.1 dielectric constant which has a thickness-to-wavelength ratio between 0.02 and 0.03. This results in a transmission loss of about 0.1 dB for the MLS elevation antenna and 0.3 dB for the MLS azimuth antenna (depending upon its maximum angle of scan). The radomes are likely to be thin and flexible to minimize the probability of ice build-up, and have a coating which will tend to avoid "sheeting" of rain on the surface by causing instead the formation of discrete droplets and discontinuous rivlets. These comments apply, of course, to new radomes. Periodic inspection would probably be required to verify that this also applies to radomes which are exposed to a sea salt environment, such as at Vancouver, or to radomes exposed to a corrosive industrial environment such as is found near Sudbury.

The extremely high dielectric constant of water, about 75 at 5 GHz, can cause high reflection losses even though only thin sheets or narrow rivlets are present. The magnitude of the transmission efficiency (Ref. 13) for the case of a typical material with a dielectric constant of 4.2 and a loss tangent of 0.014 are illustrated in Figures 4.31 and 4.32 for parallel polarization (i.e., EL antenna) and perpendicular polarization (i.e., AZ antenna). Efficiencies of from 94 to 98% are typical.

Figure 4.31 Transmission Efficiency ($\epsilon=4.2$)

Figure 4.32 Transmission Efficiency ($\epsilon=4.2$)

As the dielectric constant increases, for example due to rain or ice, the amount of reflected power increases and the transmission efficiency falls. This is illustrated in Figures 4.33 and 4.34 for the sample case of a dielectric constant of 9.0 and a loss tangent of 0.0004, showing the efficiency fallen to the 60 to 80% range. The dielectric constant for pure water at 5 GHz is about 75 ($\tan \delta = .16$) and that of fresh water ice about 3.2 ($\tan \delta = 0.0009$). This very large dielectric constant supports the contention that a layer or sheet of water forming on a radome could dramatically reduce the radiated signal power. A dramatic reduction in radiated power is likely to be detected by the MLS field monitor and presumably the MLS would then be turned off. Unless the monitor fails to detect the problem because the rain covers only a portion of the radome, the problem is not catastrophic.

Rain or ice can also introduce a squint in the beam due to refraction as shown in Figure 4.35. Table 4-16 tabulates the magnitude of the resulting squint expressed as an offset from a non-refracted beam.

Table 4-16

Refractive Material	Thickness (inches)	Offset* (inches)
Water ($\epsilon=75$)	0.04	0.034
	0.15	0.13
Ice ($\epsilon=3$)	0.15	0.11
	1.0	0.72

*Note: Calculated for worst case 60° incidence angle.

It can be seen that the maximum offset is approximately equal to 80% of the material thickness and when compared to the accuracy required of the MLS, will not contribute a significant error to the guidance angle error budget compared to the transmission loss effect previously described.

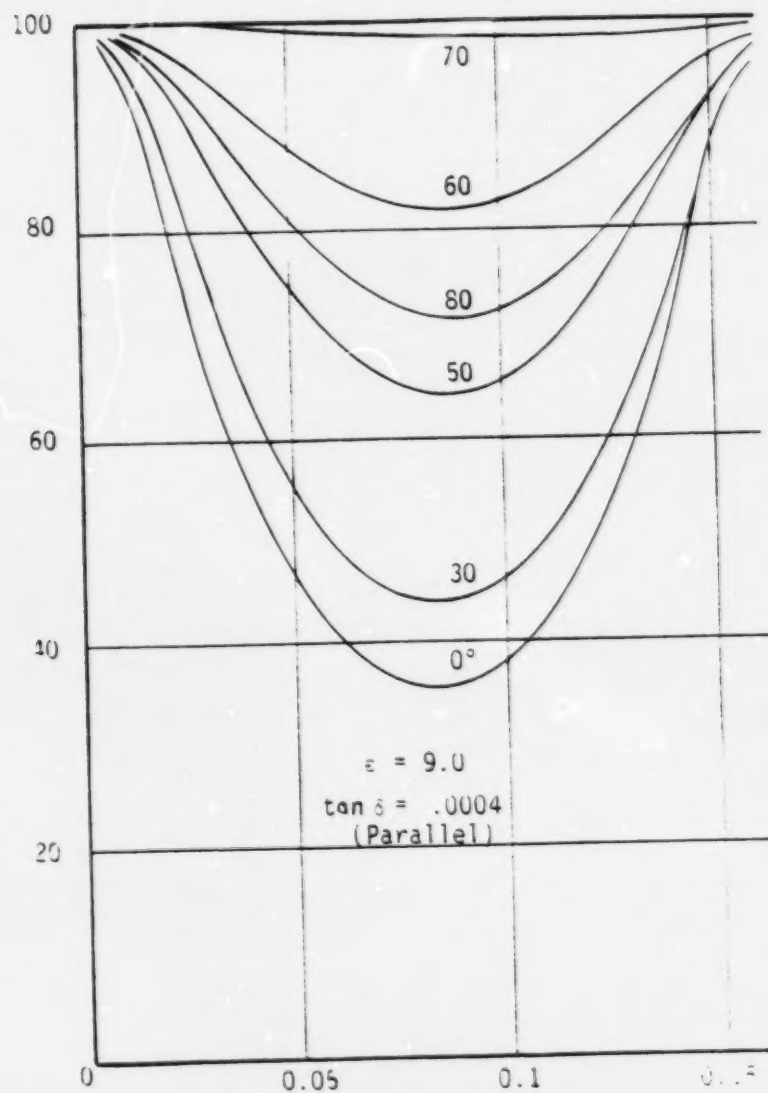
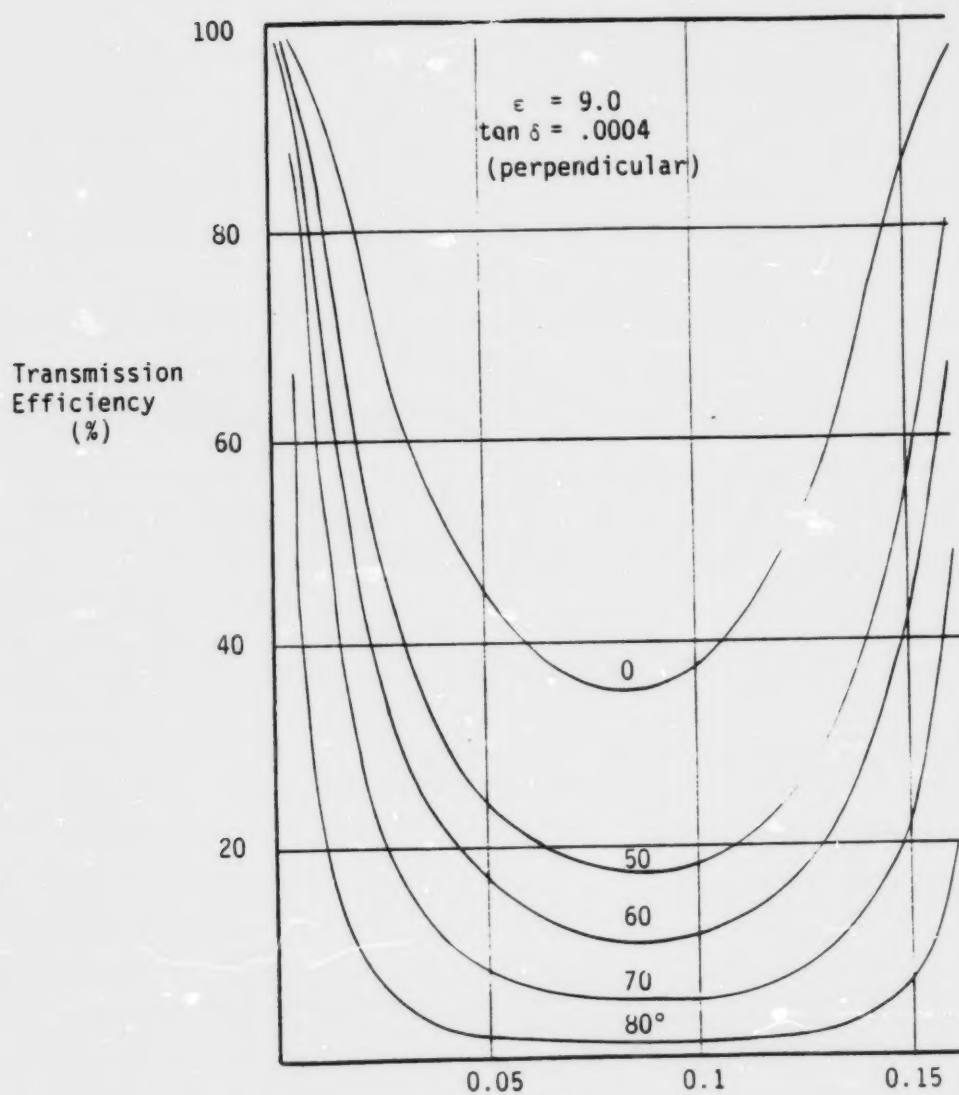


Figure 4.33 Transmission Efficiency ($\epsilon=9$)

Figure 4.34 Transmission Efficiency ($\epsilon=9$)

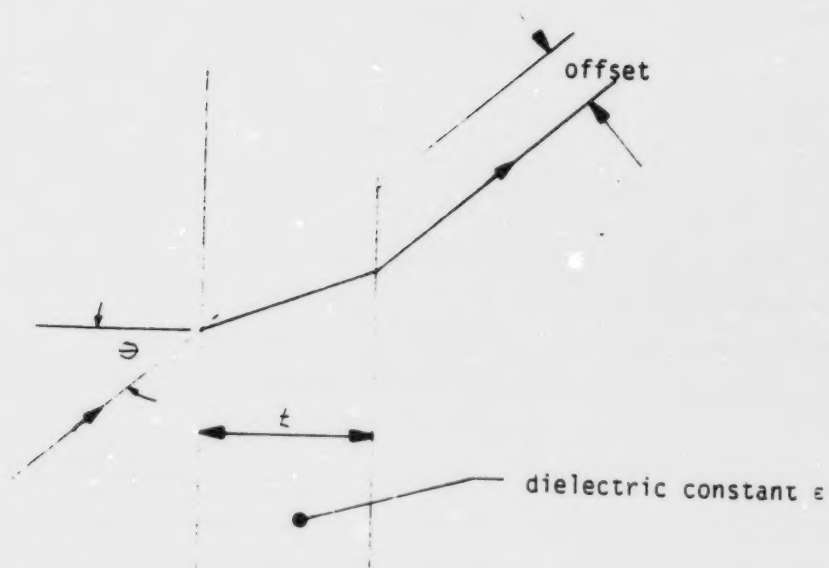


Figure 4.35 Beam Squint Due by Refraction

The above calculations postulate a problem for the MLS which is significant only if the rain forms either a real or an "effective" sheet on the radome surface. Since it is probable the radome material will be designed specifically so that rain will not "sheet", this problem might well be overcome by the manufacturer. In order to ascertain if this postulation is correct, it is recommended the MLS be tested to determine if rain will cause a significant transmission loss during rain conditions under which an aircraft might be expected to land using the MLS.

Rain may also cause localized effects on the array performance, for example, by forming "rivulets" in front of an array element. The array performance degradation is likely to be exhibited as an increase in sidelobe level rather than a significant decrease in radiated power. This result is postulated for two reasons, one because of the reduction in radiated power and two, because of the phase shift/time delay caused by the lower propagation velocity of the energy as it travels through the rain layer. The effect would be very similar to that caused by variations in element phase shifters, i.e., an increase in sidelobe level. Therefore, sidelobe level tests should also be conducted during rain conditions.

In order to carefully control conditions during such a test (particularly avoidance of multipath effects), it is recommended this type of testing be performed at a high quality antenna test range, in particular those tests associated with sidelobe level measurement.

The effect of ice buildup on a radome is not as significant unless the ice builds up to a thickness of approaching 0.1λ (0.23 inches) or more. While this could very easily occur, it is probable the ice layer would tend to build up uniformly and therefore, the effects are relatively predictable. It is, of course, possible to test and confirm the effects of uniform ice buildup at an antenna test facility, but it is more difficult to simulate uneven icing conditions that could be considered credible, i.e., probable in nature.

It is recommended that consideration be given to consulting with local experts in areas of Canada where icing conditions are severe, for example, St. John's, Newfoundland and/or Prince Rupert, British Columbia, to define the scope of the problem. (Possibly, aircraft could not land under icing conditions in any case.). If it is possible that the ice could build-up such that a monitor would not detect the degradation in performance due to the unevenness of the build up, then a problem has been identified which could be subsequently confirmed by testing.

It is further recommended that Transport Canada require the MLS supplier to test the performance of the proposed radome material under icing conditions in a laboratory environment, since some materials resist ice build up better than others. This testing should also consider salt-water ice build up, since salt water ice might form more easily on some materials. Some consideration could be given to ice prevention, either internal heating or heating cables embedded in the radome surface.

4.3.4 VIBRATION

The analysis of Section 4.3.1 shows that the antenna is sensitive to mechanical deformations in the size or shape of the array. Thus, it may safely be assumed that unless care is taken in the mechanical design of the antenna, vibration caused by wind blowing on such a large flat array could cause the guidance accuracy to deteriorate similarly.

A detailed knowledge of the antenna mechanical construction is required to predict in advance whether a particular system will be sensitive to vibration. For example, a manufacturer might apply aerodynamic design principles and avoid the problem, or include internal vibration damping so that when the radome vibrates in the wind, the vibration is not passed to the radiating elements.

However, if the array should rotate about the axis of beam scan by more than $\pm 0.04^\circ$, the guidance angle accuracy specification will be exceeded. (This corresponds to $\pm 1.4\text{mm}$ for a 2 meter flat array). Also if

individual elements can vibrate with respect to each other, the effect will be essentially identical to phase errors in the phase shifters. Since phase shift errors cause an increase in sidelobe level, this is the most probable result of individual element vibration. Reference 4 describes an analytical technique for relating random phase errors to sidelobe level performance. The result of this analysis is reproduced in graphical form as Figure 4.36. This figure shows the theoretical result of random phase errors in a Dolph-Chebyshev array consisting of 25 elements with a design sidelobe level of 29dB. It can be seen that 2.5% of the sidelobes exceed the design sidelobe level by 6dB or more when the RMS phase error is 5.7° . A phase error of 5.7° is equivalent to a vibration motion of 1.2mm RMS randomly distributed over the 64 elements.

This analysis is only indicative of the magnitude of the potential problem because vibration has a tendency to be harmonic in nature rather than random. Therefore, the vibration sensitivity could be worse than calculated above.

However, it is obvious that only a small amount of mechanical motion in the array could cause MLS performance to deteriorate. Without a detailed knowledge of the antenna mechanical design, a more qualitative analysis cannot be performed. It is clear, though, that a problem might exist and that measurements of vibration sensitivity should be performed, at least on a First Article production item basis.

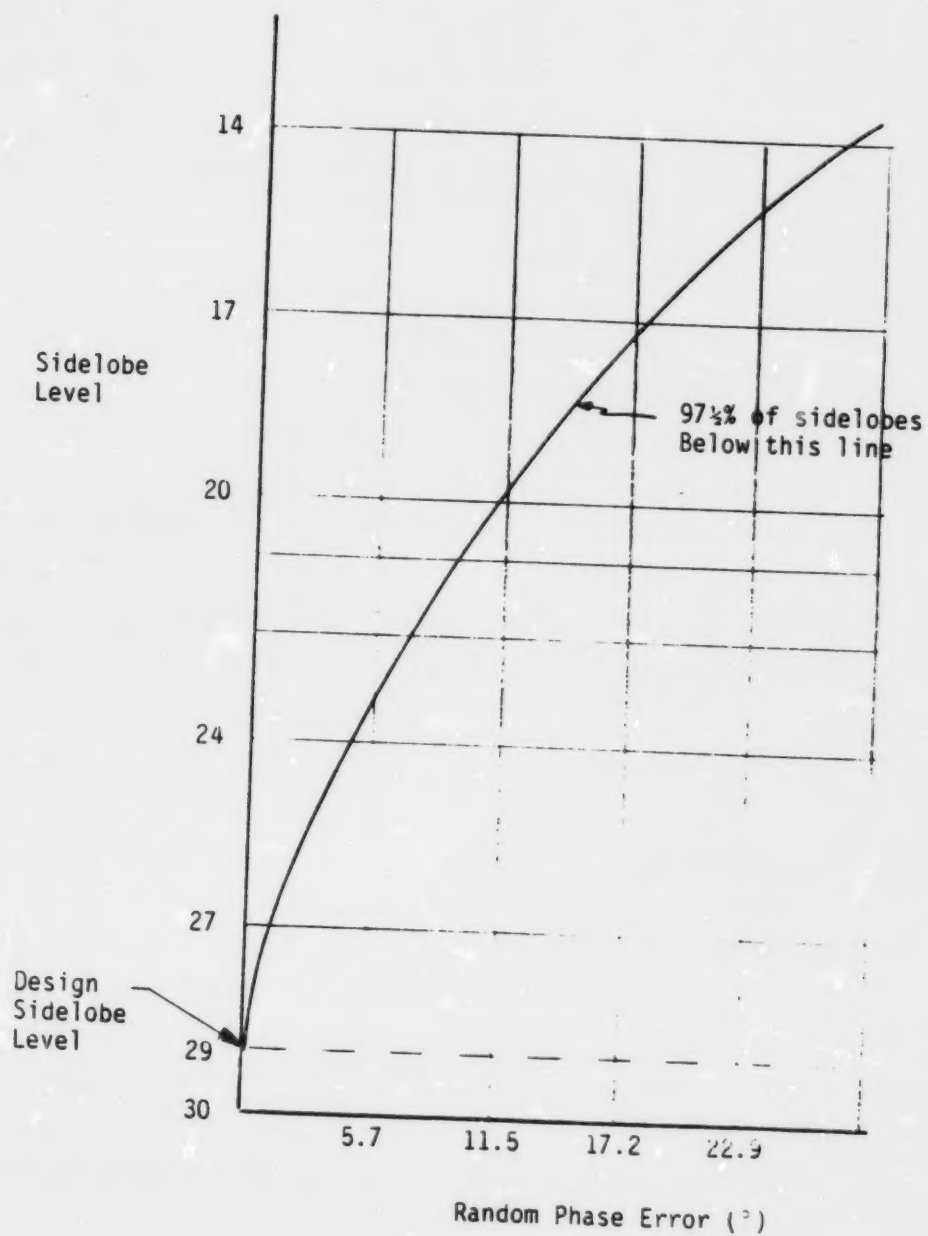


Figure 4.36 Increase in Sidelobe Level Due to Random Phase Errors

5.0 TEST FACILITY DESCRIPTION

This section of the report provides a detailed description of the required MLS test facility, taking into consideration all of the alternative measurement techniques discussed in Section 4.0.

In order to perform the wide range of tests required for the MLS, it is desirable to subdivide the test facility into three interrelated but functionally separate facilities, i.e.:

- First Article Test Facility
- Commissioning Test Facility
- Periodic Test Facility

While the Commissioning Test Set is the primary facility for ground based testing and certification of a MLS, two other equipments are needed to support this facility, i.e., a First Article Test Facility and a Periodic Test Facility. The First Article Test Facility is needed to conduct sidelobe level tests and environmental sensitivity tests on first run production models from each accredited manufacturer, while a Periodic Test Facility is needed as an "In-Service" Test Set to periodically confirm MLS performance is not deteriorating and that the MLS integral field monitor continues to function accurately.

Each of these test facilities is described in detail together with an estimate of cost.

5.1 FIRST ARTICLE ANTENNA TEST FACILITY

The primary purpose of the First Article MLS Antenna Test Facility (FAMAT) is to provide a facility where sidelobe level testing can be performed accurately without multipath interference and environmental testing can be accomplished under controlled conditions. In addition, such a facility is needed to aid in validation of both the Commissioning Test Set and the MLS field monitor subsystem.

5.1.1 TEST PARAMETERS

The FAMAT must be capable of measuring:

- Sidelobe level
- Guidance accuracy under various environmental conditions
- All spatially variant parameters

While angle guidance accuracy is the most important spatially variant parameter, the facility should also provide the capability to measure radiated power and polarization effects. This would be particularly advantageous for validation measurements.

5.1.2 FAMAT FACILITY DESCRIPTION

Figure 5.1 shows a block diagram of the FAMAT test facility. The key constituent is a low multipath antenna test range. Ideally, the antenna test range should be a far-field test facility with zero multipath. Since zero multipath is not practical, the facility should either have multipath at least 35dB down from the main lobe, or have the multipath carefully measured and controlled so that reflected multiple path signals can be distinguished from sidelobes and therefore, subsequently ignored. (The 35dB figure comes from the 30dB minimum SLL derived in Section 4.3.2, plus a 5dB margin.)

The facility recommended for these tests is the new Communications Research Centre's David Florida Lab (DFL) roof mounted antenna test facility. This facility has the following features (additional details are provided in Appendix D):

- a) Antenna test pedestal mounted on the edge of a building roof, 65 ft. from the ground.
- b) Receiving tower 1300 ft. away at a height of 200 ft. from the ground.
- c) Movable diffraction fences available for ground multipath reduction if required.

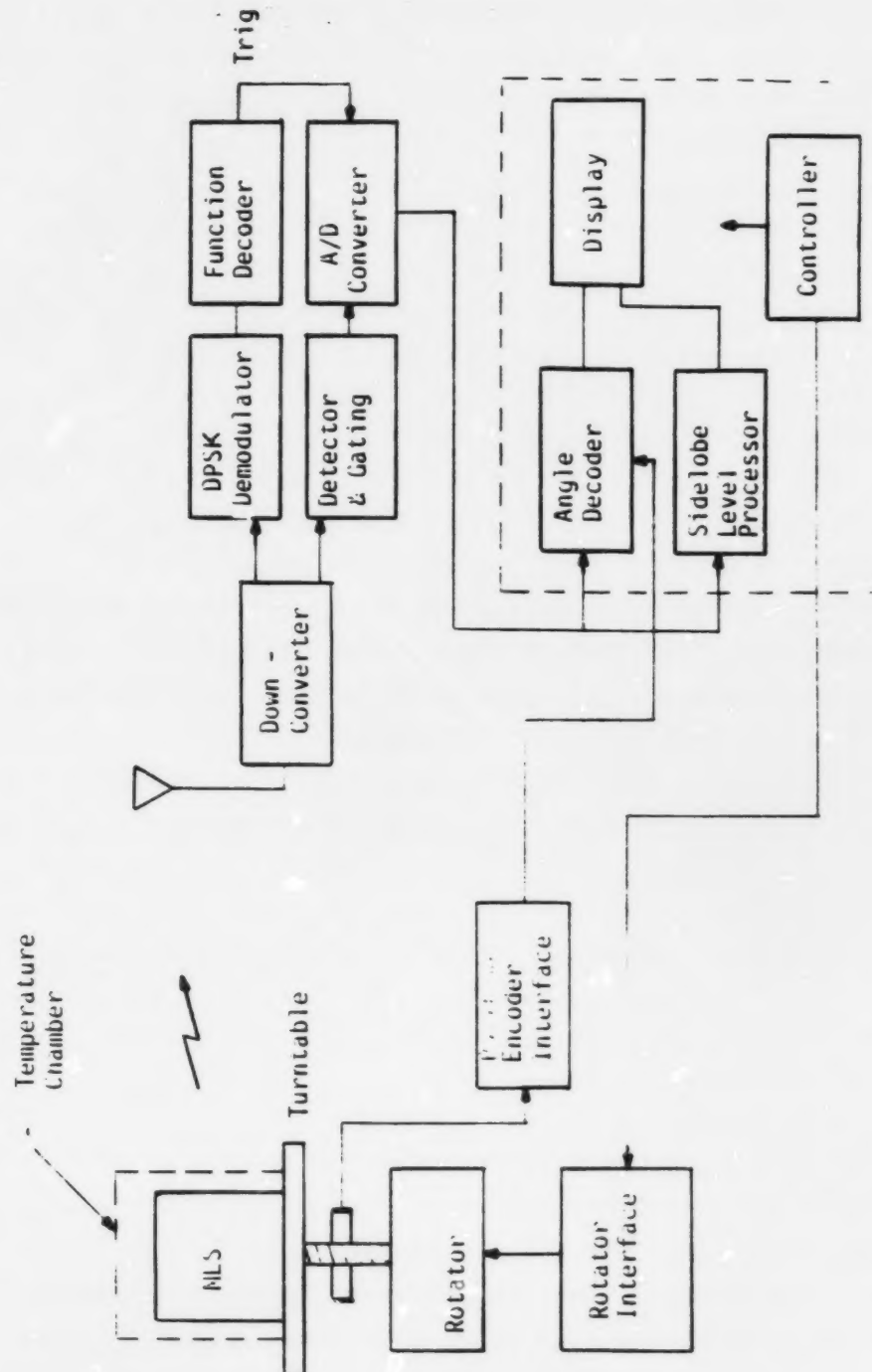


Figure 5.1 First Article Antenna Test Facility

While the facility is recommended primarily because of its low multipath, its proximity to Transport Canada users, and its reasonable rental cost, any similar facility with sufficiently low multipath performance would suffice.

In order to reduce the importance of ground reflected multipath, which, in anything but a free space facility, will always be present, the MLS should always be tested with the beam scanning horizontally. This is appropriate because the principal energy incident upon the ground will be due to the main beam itself and unless the ground surface is both asymmetrical and the reflection strong, no significant guidance error will result. Of course, there will be an error in measured signal amplitude, but this error is usually small. The more significant multipath errors caused by sidelobe reflection off vertical surfaces, can be more easily controlled by not permitting buildings in the area and maintaining the receiver and transmitter as high as possible. Therefore, the EL system will have to be measured while "tipped" on its side.

Each block in the block diagram of Figure 5.1 is described below in detail:

a) MLS

This is a complete model of the MLS to be tested with a mounting adaptor for the turntable. The rigidity of the adaptor is crucial because wind induced MLS motion must be transmitted through to the turntable and detected by the position encoder. An adaptor for the EL system will, therefore, be more difficult to construct because of the offside mount.

b) Turntable, Controller and Encoder

The turntable must have sufficient capability to carry approximately 1500 lbs. of load and withstand local wind loading on antennas up to 8 ft. long by 4 ft. wide. The controller preferably should be an open loop type with fine resolution and a remote control capability.

c) Receive Antenna

The receiving antenna is required to have a sufficiently narrow beam to discriminate against multipath. Its sidelobe level must be sufficiently low that the 35dB multipath level can be achieved with the expected ground reflectivity, with diffraction fences used where necessary. A 6 ft. diameter parabolic dish should be sufficient, mounted so that it can be rotated to vary the polarization by $\pm 30^\circ$, and, by rotating 180° , ascertain the actual phase centre to $\pm 0.005^\circ$ or better.

d) Receiver

The receiver includes a downconverter to convert the 5GHz signal to a convenient IF for demodulation. A DPSK demodulator and function word decoder is needed to provide a TRIGGER signal for gating the scanning beam. A logarithmic type detector converts the IF to a video scanning beam signal which is gated appropriately by the TRIGGER signal and then digitized.

e) Processor

The processor consists of a digital computer suitably programmed to provide the following:

- i) A command interface to start and stop the rotation of the turntable.
- ii) An angle processor to determine the beam centre of the TO and FRO sweeps, calculate the receiver position, subtract the position encoder signal and determine absolute position. Section 4.2.4 describes the beam centre-finding algorithm necessary to achieve the required accuracy.
- iii) A sidelobe level processor which is required to compute the dynamic sidelobe level during beam scan. (Described in detail in Section 5.4)

- iv) A display, either CRT or hardcopy or both, is necessary to display the results of the processing. It is desirable to display both intermediate and final results to aid in interpretation of conclusions.

5.1.3 SIDELOBE LEVEL MEASUREMENT

Computation of dynamic sidelobe levels (SLL) requires that the level that is exceeded 3 percent of the time by the sidelobes be measured, during the beam scan time but excluding the main beam. This is illustrated graphically in Figure 5.2 where $(t_1 + t_2 + t_3)$ divided by $(T_s - t_4)$ must equal 0.03.

One straightforward technique of measuring sidelobes is to digitize the scanning beam video output by using an A/D converter, then store the samples over many scans in memory. Once a statistically significant number of sidelobes is obtained, it would be possible to process the data and determine the threshold above which 3% of the data samples occur. (Note that the main beam energy must not be included in the samples.)

For example on a typical TO and FRO scan of approximately 12.4 ms, the sidelobes will occur over a duration of 12.2 msec. if a 2° beamwidth is assumed. Assuming a sampling rate of 1 MHz and repeating the sampling process 16 times to average over phase shifter errors, 200 Kbytes of memory is required (assuming 8-bit data) in order to obtain the sidelobe level information at one point in space. The dynamic sidelobe level might be expected to vary spatially with angular position in the region of proportional coverage. If it was considered essential to find the average dynamic sidelobe level over the coverage area, then for example, 200 Kbyte samples at 1° increments would have to be taken over the full 124° of proportional coverage and a memory of 24.8 Mbytes would be required. Such a memory requirement is prohibitive in terms of both cost and processing time. In order to reduce the memory requirements, it would be possible to use an analog threshold before the A/D converter to eliminate 90% to 95% of the incoming samples. This analog threshold could be determined based on the

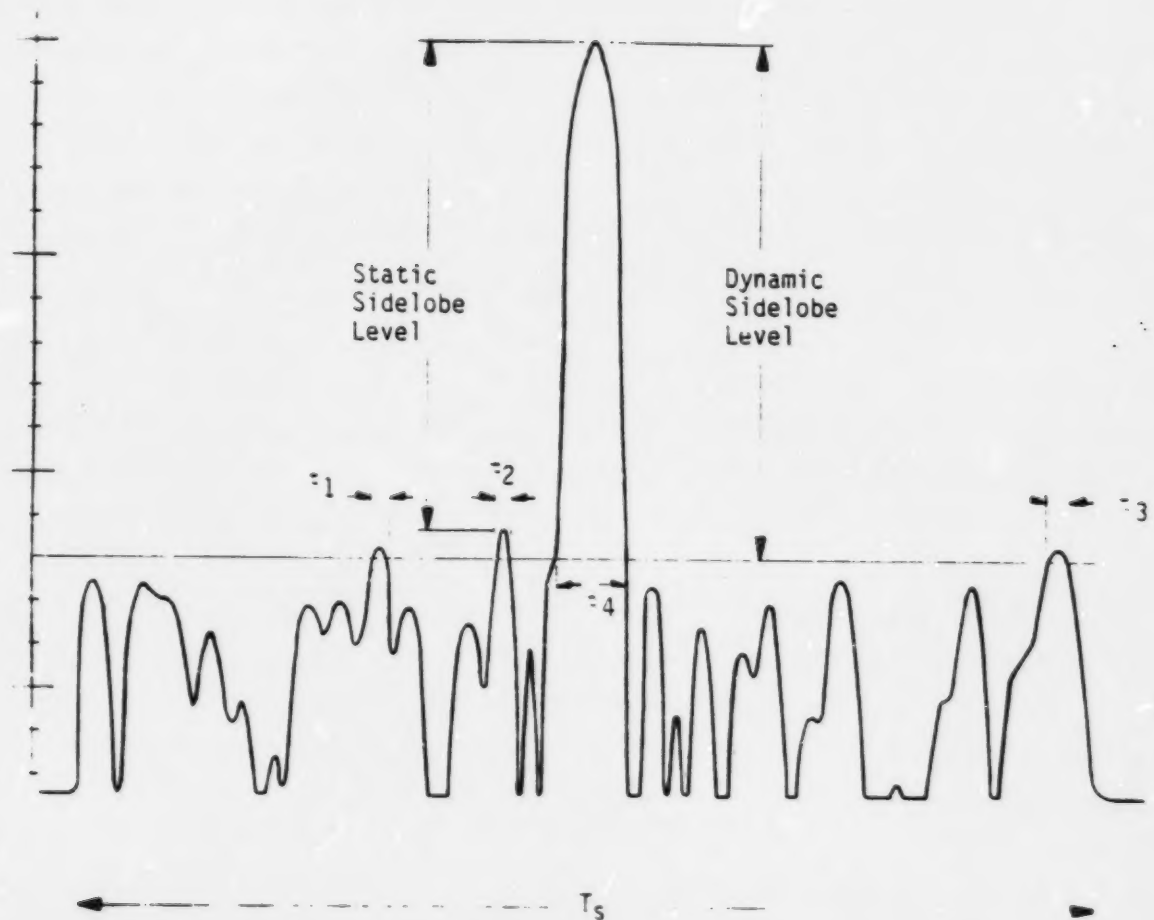


Figure 5.2 Sidelobe Level Definition

fact that the far field amplitude of the sidelobes $|F(\theta)|$ can be represented by a modified Rayleigh distribution (Ref. 14).

$$|F(\theta)| = P(r) = \frac{r}{\sigma_R^2} I_0 \left(\frac{r \cdot \bar{r}}{\sigma_R^2} \right) \exp \left[- \frac{(r^2 + \bar{r}^2)}{2\sigma_R^2} \right]$$

in which the random variation $r = f(\theta)$ is the far field amplitude at an angle of θ . Since ideally, $\bar{f}(\theta)$ is deterministic, one could condition $P(r)$ on $\bar{f}(\theta)$ and integrate over all required angles θ . That is,

$$P(r|\bar{f}(\theta)) = \frac{r I_0}{\sigma_R^2} \left[\frac{r \bar{f}(\theta)}{\sigma_R^2} \right] \exp \left[- \frac{(r^2 + \bar{f}(\theta)^2)}{2\sigma_R^2} \right]$$

The probability that $r > R$ (R is a fixed threshold) is given by:

$$P(r > R) = \int_R P(r) dr = \int_R dr \int_{-\pi}^{\pi} P(r|\bar{f}(\theta)) \cdot P(\bar{f}(\theta)) d\theta$$

The above expression could be evaluated on a computer to obtain the threshold estimate.

Alternatively, it would seem more desirable to instead compute one dynamic sidelobe level measurement for each point in space, and not perform the averaging at all. The memory requirements are not severe, and if the MLS under test exhibited a wide variation in SLL performance over the coverage, this information would be invaluable when determining anticipated multipath performance.

It should be noted one challenging aspect of the measurement technique is to ensure the main beam is excluded, but that all sidelobes are included. One technique would be to find the center of the main beam, measure beamwidth, calculate the location of the first nulls theoretically, then apply a local search routine to locate the null exactly. Since the beam data is required to be computed for the environmental tests, such an algorithm does seem practical.

It is interesting to note that the FAA have proposed an alternative technique for measuring the effect of dynamic sidelobes on multipath performance. The technique (referenced in FAA-E-2721/2, paragraph 2.4.2.3.3) involves generating a second "artificial" main beamshape and adding it to the antenna generated beam pattern, then applying the result to a MLS receiver and measuring the resulting PFE and CMN errors.

This technique is interesting because it avoids the use of the theoretical equation as described in Section 4.2.4.1. The procedure is not well explained, however, one implementation is illustrated in Figures 5.3 and 5.4. Two factors are essential.

- i) The artificial beam must have insignificant sidelobes, and, when added to the received pattern, have an amplitude greater than the received signal by amplitude A_1 so that the receiver will be "captured" by the artificial beam. (Note that $A_1 = 1\text{dB}$ for an EL system and 6dB for an AZ system according to FAA requirements.)
- ii) The relative phase between the real and artificial beams must be adjusted to produce maximum error.

The test involves "moving" the artificial beam across the beam scan period (avoiding the main beam) and noting the worst case PFE/CMN, all the while maintaining the phase to produce maximum errors. The MLS system is then "rotated" slightly and the process repeated.

This alternative technique was considered. It has the advantage, or disadvantage depending on your point of view, of requiring the use of a MLS receiver for the test. The advantage is that a theoretical equation is not required for multipath estimates; while the possible disadvantage is that the test receiver might not be typical of a "brand X" airborne receiver that it is trying to emulate for multipath effects. Since it was considered a "toss-up", the direct SLL measurement technique was chosen because it is slightly simpler to implement.

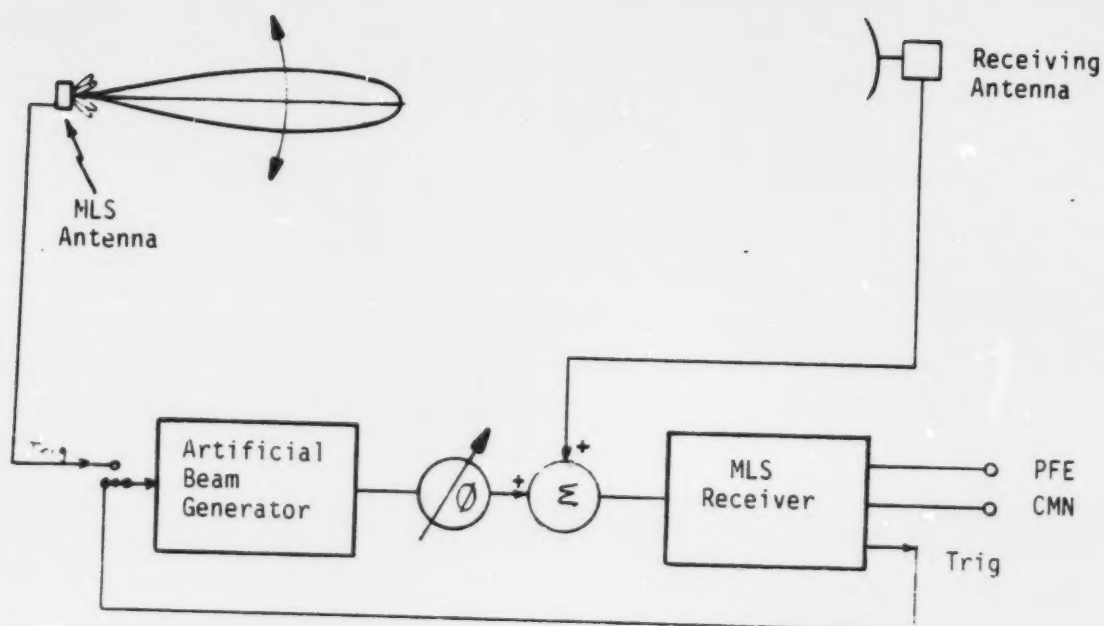


Figure 5.3 FAA Sidelobe Level Measuring Approach

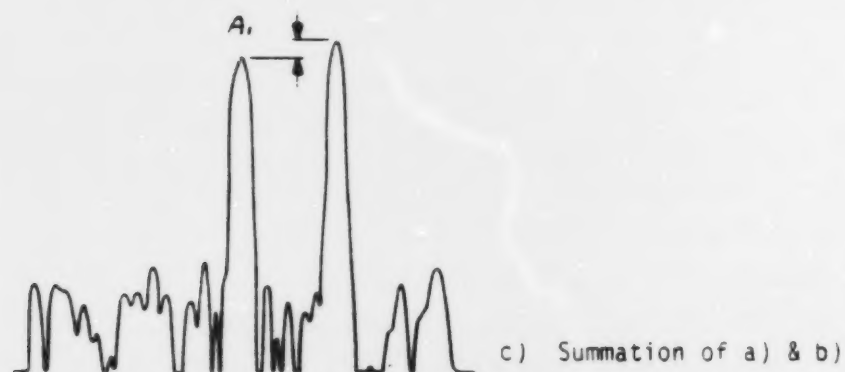
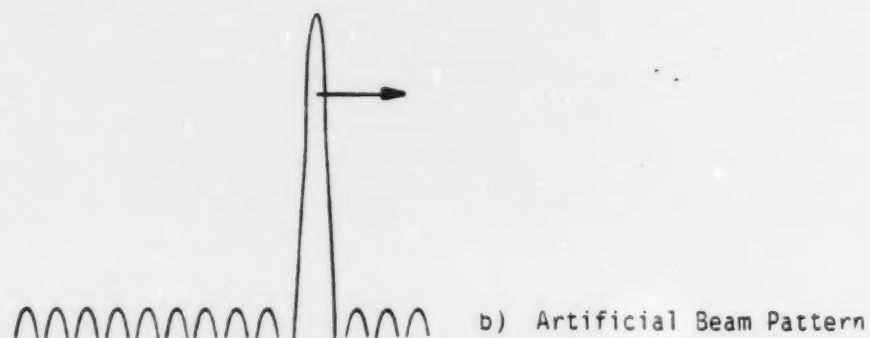
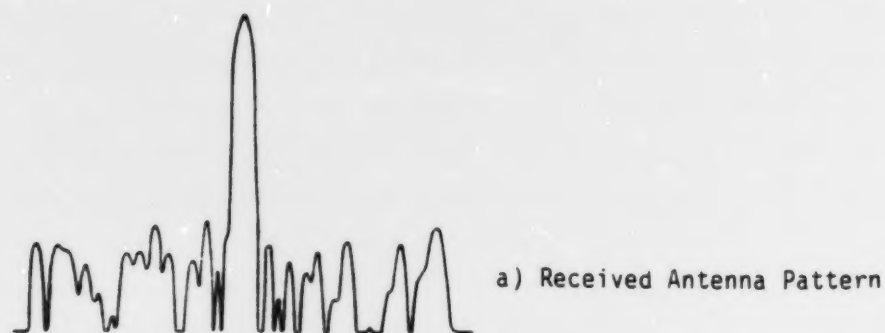


Figure 5.4 FAA SLL Test Waveshapes

It is important to realize that the FAA have imposed two controls on sidelobe performance, one is airport dependent and therefore weaker. The second is a direct requirement on sidelobe level regardless of airport and is therefore much stronger. It is recommended that Transport Canada also adopt a SLL specification that is airport independent to avoid possibly unpleasant and probably irresolvable disputes with suppliers.

Again, for emphasis, whichever measurement technique is chosen, care must be taken to assure that the measurement site is free from excessive multipath, or SLL will not be measured accurately.

5.1.5 ENVIRONMENTAL TESTS

It is recommended that tests be performed on the antenna portion of the MLS under the following environmental conditions:

- Temperature
- Simulated rain
- Humidity
- Simulated icing
- Wind-induced vibration

It is proposed that the FAMAT facility be utilized to perform the first two tests, i.e., temperature and simulated rain.

- Temperature

A structure made of fibreglass material and styrofoam insulation is required to be constructed and placed around the MLS system. The structure needs to be sufficiently small that it will rotate on the pedestal with the MLS to avoid variations in performance due to the housing materials located in the radiating field. To provide cooling, a liquid nitrogen tank may be connected to the structure via tubing, while a space heater or heat lamps can be located inside the housing to provide heating. A circulation fan may be required to circulate the air for more uniform cooling and heating.

- Simulated Rain

With the temporary structure removed, a sprayer should be directed at the radome to simulate rain. If a problem is detected, it will be necessary to confirm that valid rain conditions are being simulated (windblown or otherwise), and that the test is not unrealistic. (An effort probably should be made to simulate rain conditions no worse than those under which an aircraft might be permitted to land using the MLS.)

The remaining three tests are much more difficult to perform for various reasons. Alternative methods which might be considered for experimental testing are outlined below:

- Humidity

It is anticipated that excessive humidity might affect the transparency of the temporary structure used for temperature testing. Otherwise humidity testing could be combined with temperature testing.

Two alternatives might be considered:

- i) If the manufacturer's product is stated to be hermetic to avoid moisture entry, then hermeticity could be tested using a non-radiating test, by checking relative humidity inside and out.
- ii) If the product is not hermetic then humid air could be piped directly into the radome housing during radiation testing. After a suitable period, the airflow would be stopped until the conditions became stable, then a radiation test performed.

- Simulated Icing

The icing test might be combined with temperature tests but ice might form on the surface of the surrounding structure and affect the signal transparency.

If the test could instead be delayed until the outdoor temperature is near but below freezing and warm water applied with a hand sprayer, the test would be easier to perform. This test could also be performed at an airport using the Commissioning Test Set as a monitoring tool, however, the test results would be more qualitative in nature.

- Wind-Induced Vibration

This test cannot be done easily on the turntable because gear backlash exceeds the angle accuracy requirement, i.e., the turntable vibration would tend to dampen the MLS vibration. If the turntable could be "locked down" and a conveniently windy day awaited, such a test could be performed.

Alternatively, this test might be performed at an airport, using a tethered aircraft outside the coverage zone to generate an artificial wind.

These tests are obviously not very repeatable nor quantitative, since wind forces cannot be controlled. Ideally, a wind tunnel test should be conducted and vibration measurements performed to identify resonant frequencies of various radiating parts of the MLS antenna. Armed with this data, it would be possible to calculate the resulting errors; or possibly to construct a special vibrator to simulate worst case conditions when the MLS is mounted on its pedestal.

5.1.6 SOFT-FAILURE TESTING

The FAMAT facility can also be used to measure the degraded mode of operation usually described as the soft-failure mode. In this mode, the MLS is still operating to specification, however, due to failures in individual array elements (phase shifters, for example), the performance is degraded.

A typical test scenario would entail disabling a random group of phase shifters to simulate failure. Because this type of failure will result in an increased sidelobe level, the FAMAT facility is ideally suited to measure the results quickly and accurately.

5.2 COMMISSIONING TEST FACILITY

The Commissioning Test Facility is the primary test facility for ground based testing and certification of a MLS. The facility consists of two major subsystems, an antenna subsystem and a receiver/processor subsystem. The antenna is to be mounted on 15 meter moveable erectible tower, preferably trailer mounted. The Receiver/Processor unit should be mounted in a van which is equipped to provide primary power and can be easily moved over the entire measurement zone.

Figure 5.5 illustrates a typical test measurement zone for the Commissioning Test Facility showing suggested measurement points. Several additional measurement points would need to be selected at random to verify performance over the entire zone.

5.2.1 ANTENNA SUBSYSTEM

The Antenna Subsystem can be further subdivided into three units, i.e.:

- Tower
- Antenna
- Antenna Locator Unit

5.2.1.1 Tower

The analysis of Section 4.2.2.3 concluded that ground based measurements should be made in the quasi-near field of the MLS antenna, i.e., at a distance of about 30 to 45 meters in front of the array. In order to measure the spatially variant parameters, the tower will have to be erectible to a height of 11 to 15 meters maximum and mounted on a trailer or

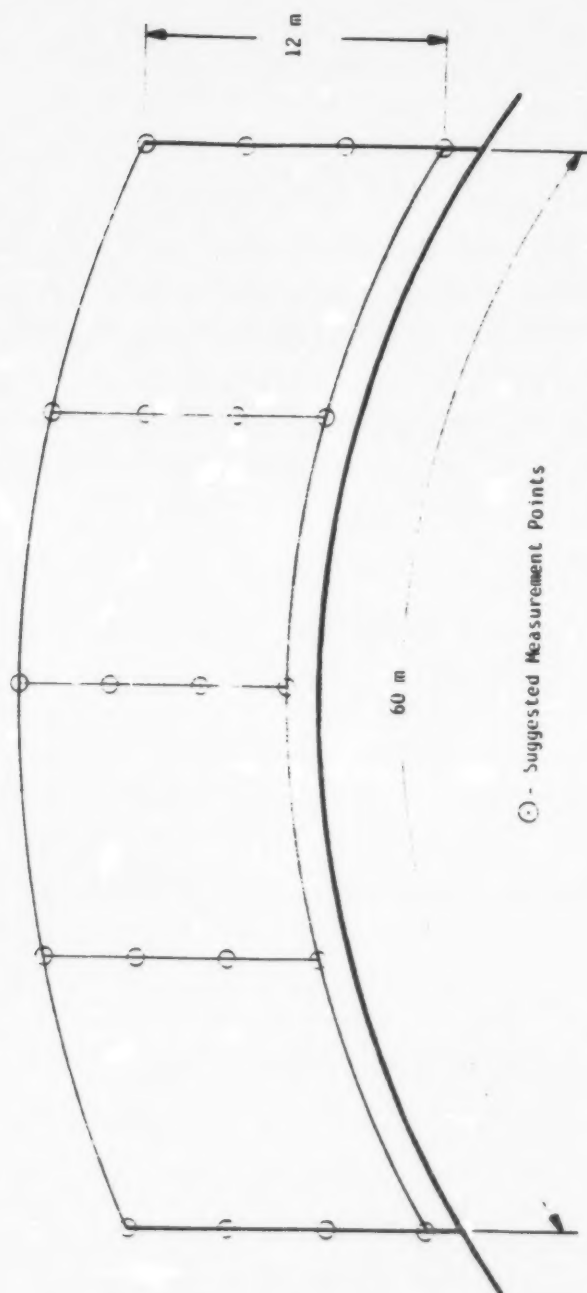


Figure 5.5 Commissioning Test Measurement Zone

vehicle so that it can be easily moved over the wide test zone at each of the two (AZ&EL) MLS sites. While it might be advantageous to have the tower guyed in some manner from the point of view of stability, it would be more tedious to raise and lower and more manpower would be required. It is obvious that the expected wind conditions during the test will significantly affect the decision.

A preliminary analysis suggests that

- i) Tubular style compressed air erectible towers typically have a circular cross-section of 10 to 18 cm. (4 to 7 in.) and are therefore likely to be less stable.
- ii) A triangular cross-section winch-erectible tower should be considerably more stable since the cross section is typically 25 to 40 cm. (10-16 in.)

The tolerable level of motion of the antenna is also important. It is estimated that a movement of up to 100 times the required position accuracy is trackable, i.e., $100 \times 3.6 \text{ mm} = 36 \text{ cm. (14 in.)}$ peak to peak. It is recommended that a typical triangular shaped winch erectible tower be rented, equipped with a dummy antenna and erected on a moderately windy day to the maximum height. A theodolite, also rented, could be used to estimate the resultant swaying and rotary motion. It seems probable that under ordinary conditions guying is unlikely to be required, but at exceptionally windy locations the tower should be guyable, although the guying may only have to be implemented on one side and at maximum tower height.

In order to avoid possible ground multipath, it will be necessary to design the tower to allow the antenna to be raised and lowered easily. It is, therefore, proposed that the upper section of the tower include a guide track so the antenna can be moved along this track. Two possible techniques for consideration would be:

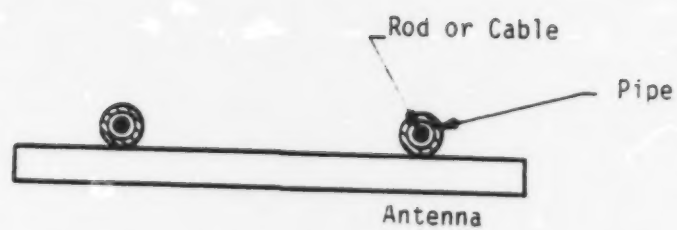
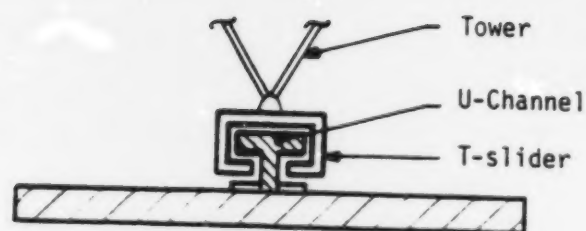


Figure 5.6 Suggested Antenna Mounting Techniques
(Cross-Section View)

- A U-channel be mounted on the tower with a T-shaped slider mounted inside such as illustrated in Figure 5.6a.
- Two tightly strung cables be mounted on the tower with hollow tubes fitted over the cables, as illustrated in Figure 5.6b.

5.2.1.2 Antenna

The recommended antenna is a trade-off between a physically large antenna with good multipath rejection and a small antenna which minimizes wind resistance. An equally important consideration is that the antenna must be mechanically very sturdy, since mechanical distortion will typically shift the antenna phase centre and degrade the guidance accuracy measurement.

There is an optimum size for the probe antenna which is to be used in the tests. At 30 m (100 ft.), 30 cm (1 ft.) is about 0.6° , so if a 1.2 m (4 ft.) diameter probe antenna were used, its width would be about equal to the 2° half-power beamwidth of the MLS azimuth antenna. If the probe antenna illumination by its own feed system had the same amplitude distribution as the illumination on its surface from the MLS antenna when the beam half-power points intersect the probe antenna edges, then all of the incident power would be accepted. This can be most easily explained by noting that normally the power incident upon an antenna is in the form of a plane wave and the receiving antenna accepts that part of the plane wave which matches its aperture illumination and reflects the rest. When the probe antenna aperture illumination matches the incident illumination, the response is peaked. The interaction between the MLS and probe antennas is a convolution. (The effect is similar to the convolution between two squares which has a triangular form which peaks when the squares are coincident.) Ordinarily, antenna patterns are not considered as convolution responses between the transmit and receive antennas because each antenna aperture occupies such a small angular portion of the other antenna's far field radiation pattern. However, in the proposed MLS quasi-near field measurements, the convolution response must be considered.

In determining the optimum illumination for the probe antenna, a series of computations will have to be made to determine the aperture size and illumination shape which provides the optimum response for the circuitry which determines the beam center. The possibility of using two different antennas, one for the azimuth and one for the elevation, will also be considered because probe antenna aperture illuminations from the two antennas are different, i.e., the azimuth MLS beam is broad in elevation but narrow in azimuth while the elevation MLS beam is broad in azimuth and narrow in elevation.

An array type antenna is considered more desirable than a parabolic reflector type because it is more stable mechanically. One desirable property which the probe antenna should have is a constant center of illumination, i.e., the phase center should not change after the probe antenna has been calibrated. The probe antenna may be checked by "tumbling" (rotating 180°) and comparing the measured MLS beam position prior to every sequence of measurements to verify that the phase center has not changed. If a parabolic antenna were used, a change in aim of the feed horn will change the apparent position of the phase center on the reflector, which is difficult to detect by visual means. The array type probe antenna has the advantage that a small high intensity light can readily be placed coincident with the phase center to facilitate automated positional tracking of the probe antenna by a CCTV camera.

It is desirable to assure that the probe antenna is peaked up on the beam of the MLS antenna. One way this can be accomplished readily is if a monopulse type probe antenna is used. When such an antenna is switched to the difference mode and adjusted in azimuth and elevation for the deepest null in the difference pattern, the sum pattern peak will be directed towards the phase center of the MLS antenna. In terms of illumination of the probe antenna aperture by the MLS antenna, adjusting the probe antenna difference pattern for deepest null is the same as adjusting the probe antenna to minimize the phase slope across its aperture.

As a result of a preliminary analysis, it is recommended that a flat rigid symmetrical array antenna be utilized, designed with a tapered illumination so that sidelobes will remain low. (A slotted waveguide structure should be a good choice because of structural rigidity and low wind resistance, plus a light source can easily be located at the phase centre.) Figures 5.7, 5.8 and 5.9 illustrate the pattern for a typical square array with a Taylor distribution, for different sizes of 45, 75 and 120 cm. respectively on a side. It can be seen that the array beamwidth varies from 4° to 9° and that the first null is 4° to 12° off the beam centre.

Figure 5.10 illustrates a typical airport scenario with the MLS phase centre about 2.5 m (8.2 ft.) above the local ground level. At a distance of 38 m (120 ft.), the zone of specular reflection is offset from the main beam by about 8° . If an antenna size were arbitrarily selected such that the first null is aimed at this zone of specular reflection, an array size of about 60 cm. (24 in.) square would be appropriate. It is important to realize that rough ground, such as may be expected in front of an MLS antenna at an airport, will cause the ground reflections to be of a diffuse nature rather than specular, and that, particularly for the elevation antenna, the primary reflections will be due to sidelobes. Therefore, the reflections might maximize at any arbitrary angle, and therefore the sidelobe performance of the measurement antenna should be designed to be 20 dB or more down from the main lobe to control multipath.

Because the ground reflections at the EL MLS site are most likely to cause guidance angle measurement errors, these reflections may have to be carefully controlled. Figure 5.10 illustrates the addition of a diffraction fence to the MLS site to reduce the reflections. Particularly bad reflection geometry may force the test to be performed at a different distance, for example, 46 m (150 ft.) instead of 38 m (125 ft.). This distance could only be determined experimentally since the problem originates due to specific sidelobes.

As noted previously in Section 4.3.4, significant pointing errors will occur if the measurement antenna is located at 15 m (50 ft.) or less from the MLS due to antenna defocussing. Errors are less than 0.0049° at 30 m (100 ft.) so this is the minimum recommended measurement range unless corrections are applied.

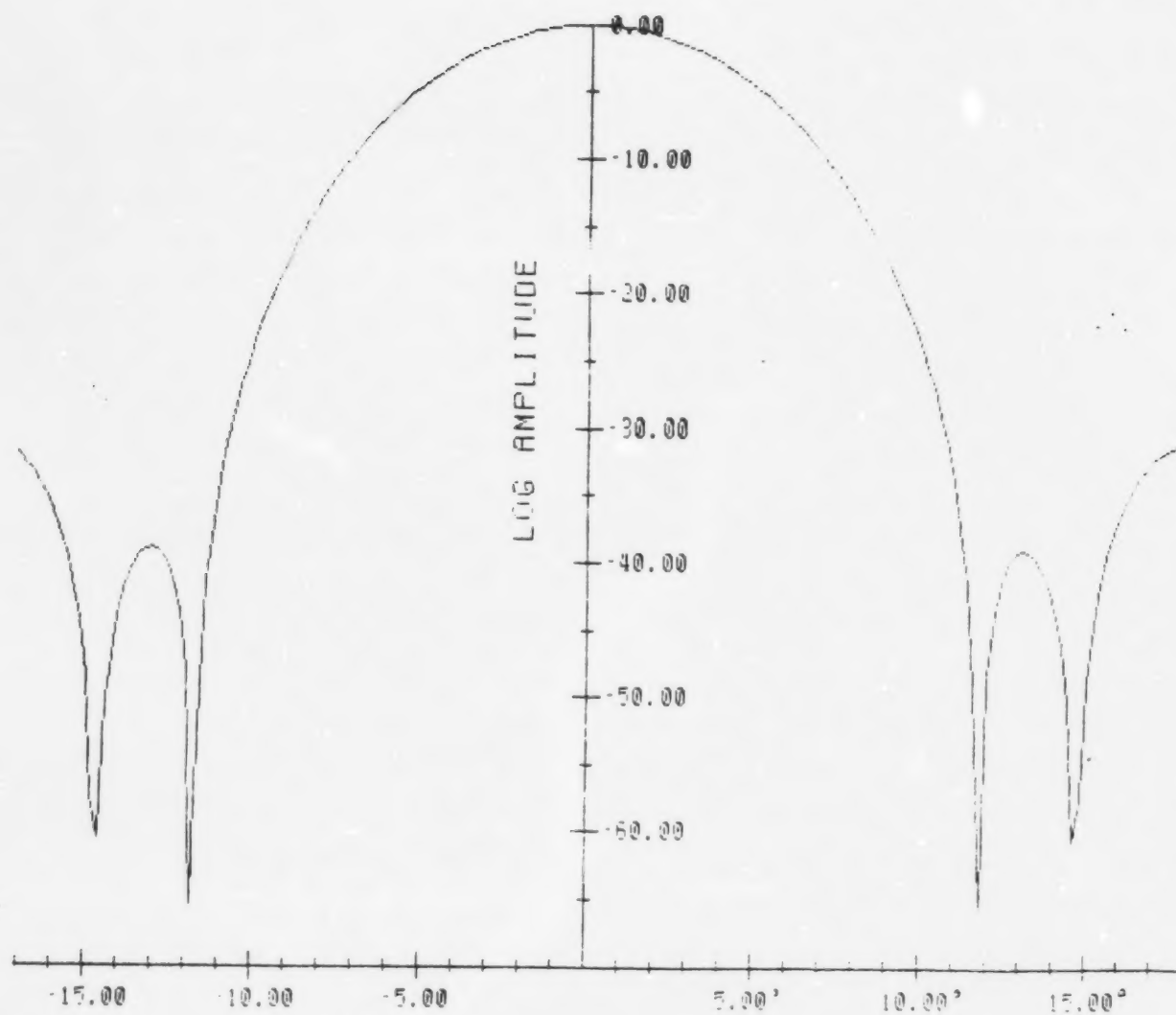


Figure 5.7 45 cm. Array Pattern

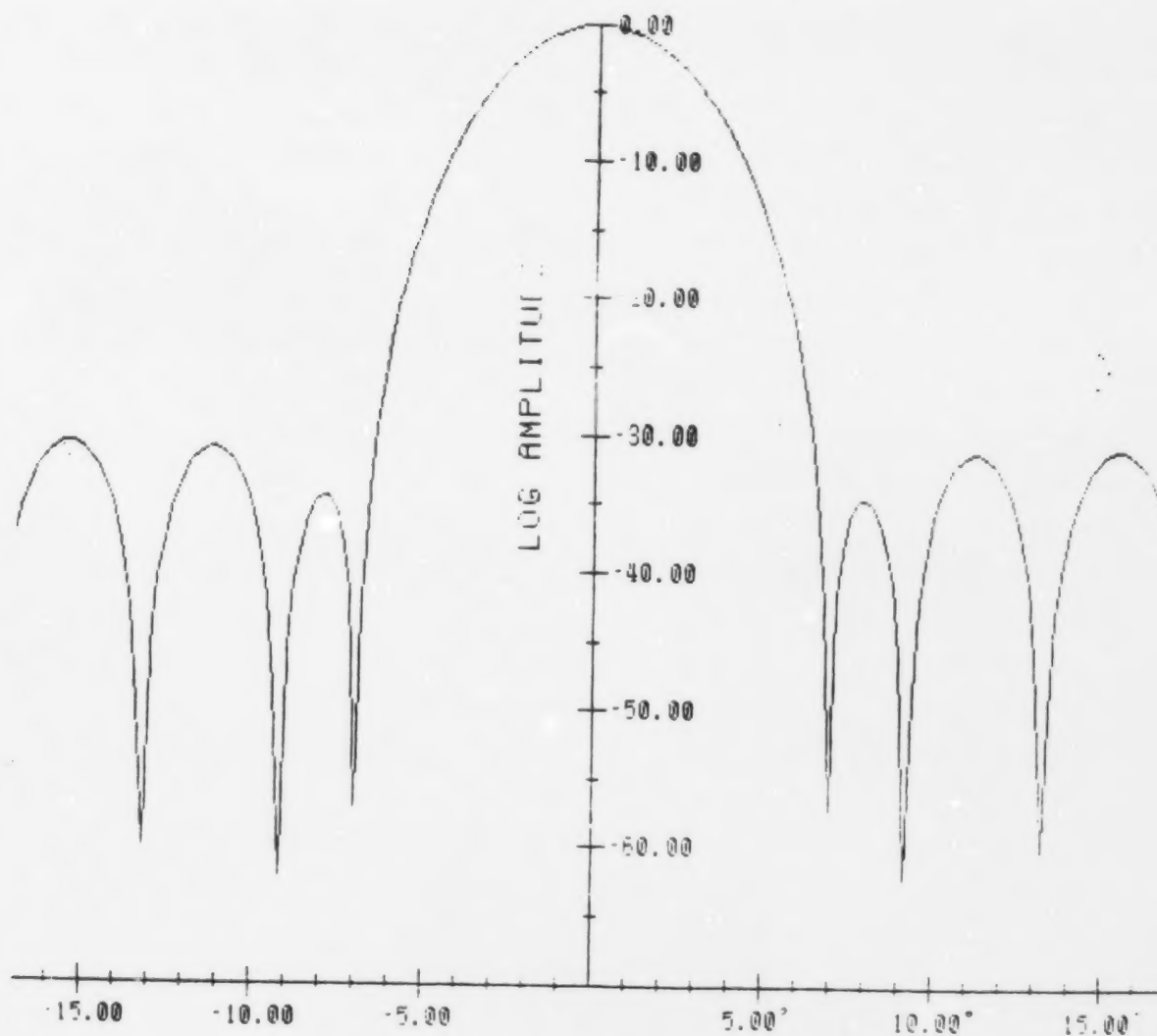


Figure 5.8 75 cm. Array Pattern

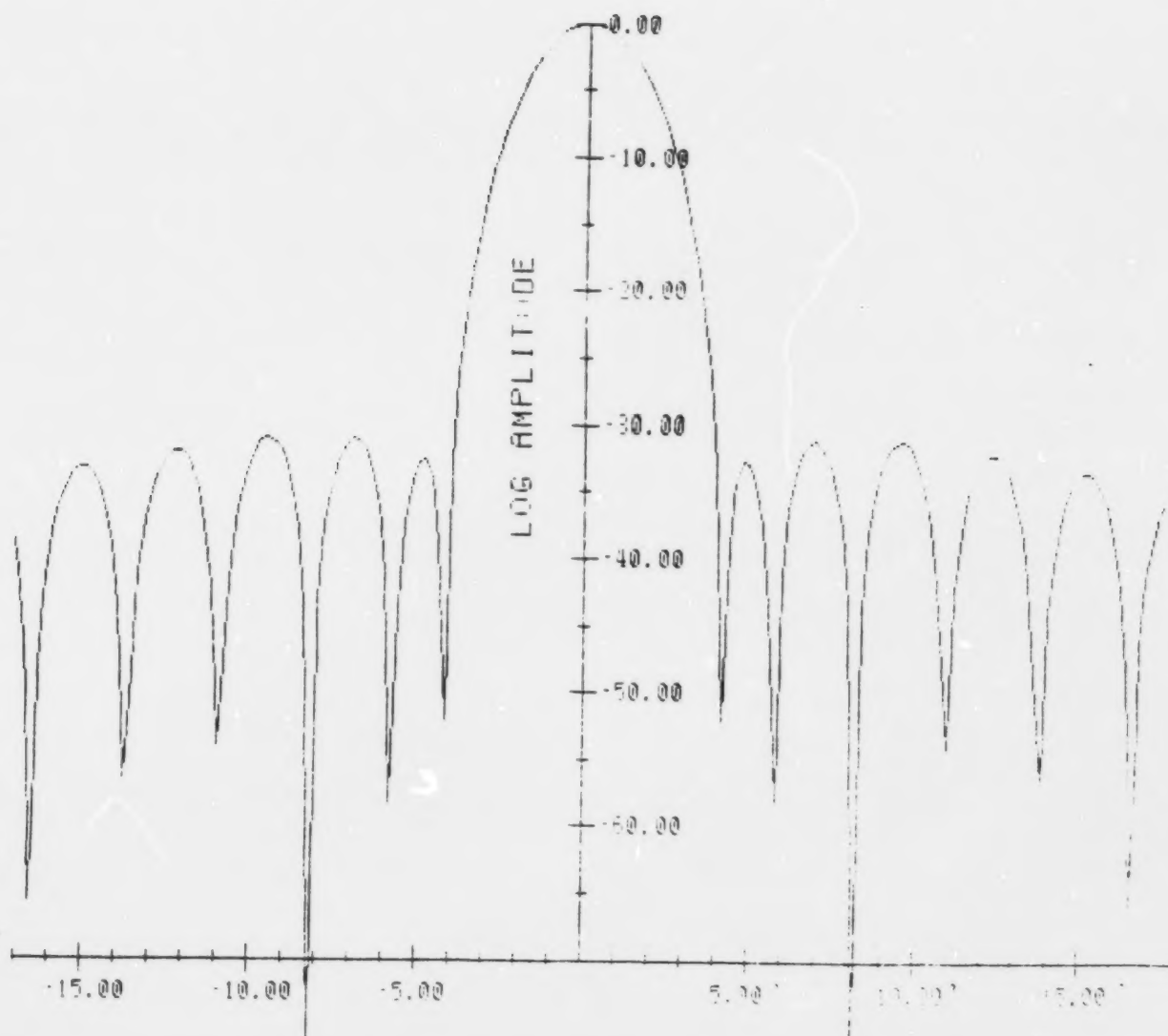


Figure 5.9 120 cm. Array Pattern

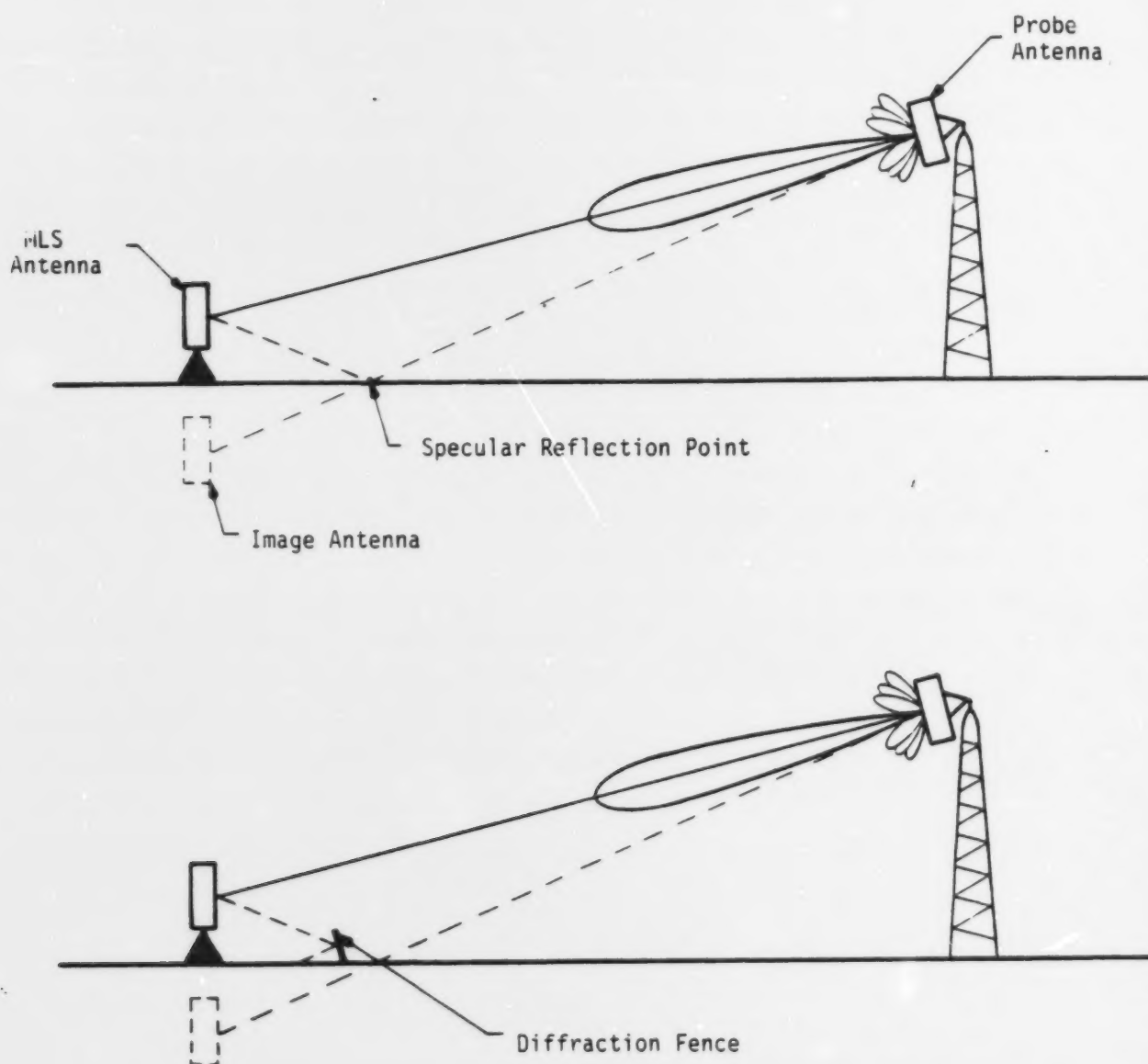


Figure 5.10 Use of Diffraction Fence to Block Reflections

At first glance, the interferometer type dual antenna concept should offer superior performance because the output beamwidth is reduced by about an order of magnitude, which should reduce the processor measurement errors significantly. However, it is also apparent that the construction of a dual antenna would have to be extremely rigid, or mechanical vibration could cause guidance errors due to shifts in the relative phase centres of the two antennas. This concern would also apply to the cables connecting to the 180° difference hybrid and the hybrid itself. Temperature stability of the structure, cables and hybrids would also be crucial. As a consequence, the approach is not a clear winner, and a more detailed investigation into the trade-offs will have to be made before this alternative can be recommended.

5.2.1.3 Antenna Locator Unit

It is recommended that some experimental tests be performed to determine the movement and rate of motion of a typical erectible tower under windy conditions. This will aid greatly in determining the optimum type of antenna location device.

However, a preliminary analysis suggests that the tower (horizontal) motion will be primarily at low frequency (i.e., less than 0.5 Hz) due to the length of the tower and the reasonable torsional rigidity expected due to the triangular shape. Since little or no vertical motion is expected, tracking may not be required for EL antenna tests.

Assuming this analysis is correct, manual tracking could be considered practical if the main constraint were financial. However, considering that many airport systems (i.e., approximately 160) have to be commissioned, manpower requirements might be of equal importance. Therefore, an automatic tracker should be strongly considered.

The optical tracker seems ideally suited for the high accuracy tracking required. The system consists of a high intensity light (for example, a halogen bulb) mounted at the phase centre of the antenna and a tracking camera located at the MLS. For the AZ MLS, the tracker should be located on the vertical centerline of the array and for the EL antenna, on the

horizontal centerline of the array, so that the motion in the direction of scan can be tracked without offset corrections. A CCTV camera with a suitable telephoto lens will be needed to provide sufficient magnification that the position can be resolved to at least one pixel in an 200 x 200 pixel TV image. This, of course, limits the amount of motion that is tolerable so that the image remains on the screen. If the motion is in excess of this limit, a high resolution camera, say 800 x 800 pixels, can be utilized, although the cost would increase rather dramatically.

A closed-loop servo controlled system can be compared on a cost versus performance basis to an open loop video tracker. The higher cost of the servo system can be traded against the calibration costs of measuring the lens error over the entire screen area and storing the results in a PROM or similar storage device. In fact, a combination scheme might be optimum, combining a low cost, low acceleration servo loop with a video pixel tracker, where the beam position is the summed output of the low tracking rate servo and the high tracking rate video.

Other considerations, such as the need for a remotely controllable pan-tilt for semi-manual acquisition of the target might also affect the desirability of this option. The output of the tracker should ideally be in digital form so that it can be fed directly into the Receiver/Processor controller for decoding and subsequent antenna position correction. A theodolite will be needed with the video tracker to define the mean location of the target. However, the servo system can provide absolute accuracy assuming a survey marker is provided within the focussing range of the camera/lens combination.

There is a limitation to the tracking accuracy of an optical tracker due to atmospheric refraction (assuming that, if operation in fog or heavy rain is required, a higher intensity light source would simply be used). The refractive effect is due to differential heating of air layers somewhat similar to the effect that causes mirages. On very hot days, hot air rises off the hot earth and either air layers or air turbulence can result due to winds. A preliminary analysis suggests the refraction errors will be less

than 0.005°, however, the result is temperature dependent. If the tests were done over a black asphalt surface such as a runway, the accuracy is more likely to be affected than if the test is done on a rough grassy field (which is more probable because of the MLS location). It would be advisable to analyze this potential problem in more detail in relationship to airport sites in Canada where heat could be a problem, Lethbridge, for example. It would seem reasonable to delay the test either to a cloudy day or to early morning hours, thereby avoiding the potential problem at a reasonable cost.

5.2.2 RECEIVER/PROCESSOR SUBSYSTEM

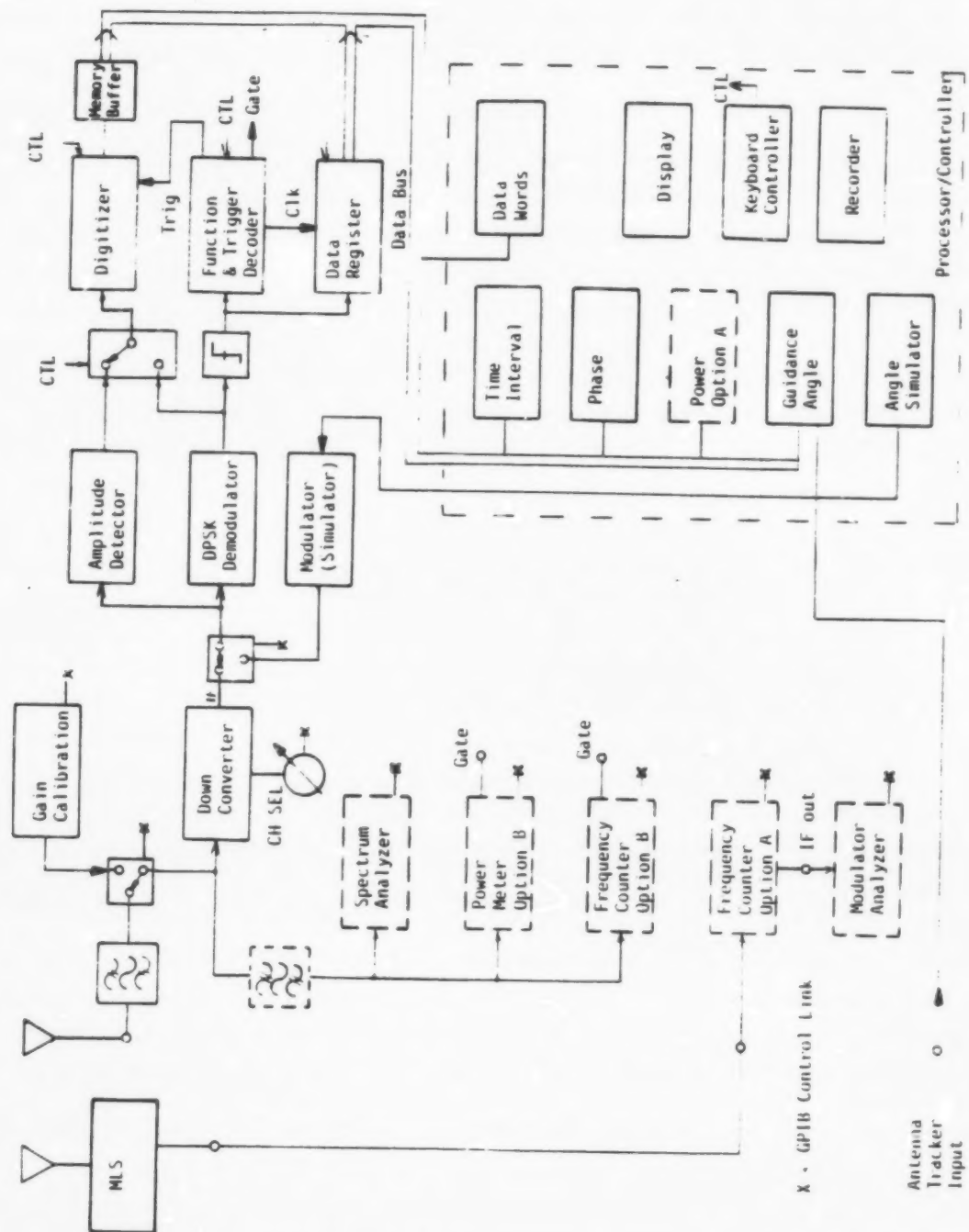
The Receiver/Processor Unit is required to be a transportable equipment, mounted inside a van or mobile home with a suitable self-contained power supply, either battery or motor generator type. Connections to the outdoor mounted antenna and tracker units should be through a weatherproof connection panel. (The tracker unit could use a VHF data link, however, it is doubtful this would be necessary or cost effective, unless the tracker was also used for Flight Inspection aircraft tracking and the link was already included.

A block diagram of the CTF is shown in Figure 5.11. Each block is discussed in detail in the following paragraphs:

a) Frequency Measurement

Two options are shown for measurement of frequency. Option B is the preferred measurement technique because it is more accurate and frequency stability can be measured as well. However, this approach requires a MLS auxiliary output and, while this study will recommend this output be provided as an addition to the MLS, it may not be available as a cost effective option.

The MLS auxiliary output is required to be a sample of the MLS 5 GHz CW output prior to either pulse or phase modulation. It will, therefore, be necessary for the MLS manufacturer to prove by analysis or measurement that the modulation process does not affect the frequency accuracy or stability.



5-29

Since the auxiliary signal is CW, a conventional frequency counter such as a HP5342A can be used to measure frequency to the required accuracy.

Short term frequency stability measurements are more difficult, however, if the counter were ordered with an ultra stable optional time base (i.e., 1×10^{-10} for 1 second), the auxiliary IF output should be a short term stable down-converted signal that it could be used to measure short term stability. One method of measuring short term stability would be to apply this IF output signal to a modulation analyzer, such as the HP8901A and measure the FM performance over a 1 second period. This method should be investigated in more detail to confirm the necessary stability is achievable.

Option B is a less preferred method of frequency measurement (as noted in Section 4.2.3) because the best case accuracy is ± 1.2 KHz, which is barely adequate. In addition, an external gating signal must be applied to activate the measurement of the pulse modulated frequency at the appropriate time. A frequency counter designed for gated pulse modulated signals, such as the HP5345A/HP5356A, will be required.

As previously noted, measurement of short term stability of a pulse modulated signal is extremely difficult and cannot be done with commercial equipment. If this option is deemed essential, a custom circuit will be required to be designed and built.

If Option B is selected, a special filter will also be required to prevent adjacent channel interference from interfering with the measurement. This special filter could be deleted if the antenna's directivity can be used to reject interferers, a solution which is site dependent.

b) Power Measurement

Again two options are shown. Both options are included because a more detailed cost trade-off is needed to determine which of the two options is the most cost effective.

Option B uses a peak pulse power meter such as a General Microwave model 478. An external gating signal must be applied to measure peak power at the appropriate instant. Again, a special filter will be required to reject adjacent channel interference, although as noted previously, the directivity of the antenna can be used to reduce the problem.

Option A requires that the measurement of peak power be done after down conversion, detection and digitization. In order for this measurement to be accurate, the gain of these intermediate blocks must be calibrated. Therefore, a module labelled "Gain Calibrator" has been included so that the measurement can be checked against an absolute power reference. The gain calibrator must be a tunable, variable power, stable power source at 5 GHz, while the power measurement is to be performed in software in the Processor/Controller.

The major advantage of Option A is that the spectrum analyzer (shown as an option as well) is not needed, since the down converter needs only to be offset in frequency and the out-of-band power measured using the Option A power meter.

While the apparently higher price of Option B (which includes the spectrum analyzer) makes this option less desirable, a close examination of the price differential is needed as a confirmation before committing to this approach.

c) Down-converter, Detector and DPSK Demodulator

These units were discussed in some detail in Sections 4.1.3, 4 and 5 and all the comments apply directly. Effectively, there are two choices. One is to use a commercial downconverter, such as a MITEQ model, and construct a detector and DPSK demodulator using off-the-shelf subsystems. The second choice is to purchase a commercial MLS Receiver, modified to provide the necessary outputs. The decision can be made on the basis of cost and flexibility. (The MLS Receiver has the advantage of presumably including a Function/Trigger Decoder Module. However, the Receiver might have to be extensively modified to provide the intermediate outputs.)

d) Digitizer, Function Decoder and Data Register

The Function Decoder consists of relatively simple serial-to-parallel shift registers and comparators implemented using digital logic. The Function Decoder is required to generate gating signals upon receipt of the selected function ident code. The gating signals gate the received data words into the Data Register and the analog video signals into the Digitizer, the gating sequence being selected by the Controller.

The digitizer performs two tasks, one is digitization of the scanning beam waveforms necessary for guidance angle computation. The second is digitization of the DPSK Demodulator output to measure pulse risetime, duration and phase shift. The digitizer should be designed with maximum flexibility to set the sampling rate at the optimum rate for each waveform (i.e., excessive rates cause memory overload and undersampling leads to aliased data). Sample rates of from 0.2 to 1 megasample per second are considered appropriate.

The controller will be required to generate the command signals to these units so that the tuning, data format, etc. are sequentially input to the Processor Unit for each of the MLS functions. (Note that command signals are designated CTL in Figure 5.1.)

It should be noted that a digital oscilloscope can be used as a digitizer. However, it has been observed that the transfer data rate from these units is generally relatively slow. Before a custom digitizer was selected, the current off-the-shelf waveform digitizers should be examined for transfer speed and price to provide the optimum cost to speed ratio.

e) Processor/Controller

The Processor/Controller should be designed on a menu format so that an operator can pre-load into memory specific test sequences to be performed. Once a complete schedule of test sequences is loaded, the system should be ready to automatically run the schedule with little or no further input from the operator. For maximum design flexibility, the controller will control the various instruments and subsystems by means of an General Purpose Interface Bus (GPIB) or a parallel bus (CTL), as appropriate. This will ensure that later system add-ons can be accommodated with ease.

Various software algorithms will need to be prepared to handle the following processing tasks:

- i) Data Words - The incoming data stream is required to be decoded and displayed.
- ii) Time Interval - Various rise time and pulse durations are required to be measured.
- iii) Phase - The differential phase shift ($180 \pm 20^\circ$) must be measured.
- iv) Power - If this option is selected, the peak power in DPSK, OCI, clearance, and scanning beam pulses must be measured. An automatic calibration run should be included as well.
- v) Guidance Angle - An optimum algorithm necessary to determine beam center is required to be implemented. Again an MLS Receiver might be used for this purpose, however, the accuracy requirements ($\pm 0.005^\circ$) are three times as stringent as required to meet the ICAO/RTCA airborne receiver requirements. Therefore, it will be necessary to confirm the accuracy is realizable without employing a more sophisticated algorithm.

In order to determine the actual PFE/CMN, it will be necessary to "subtract" the current position of the phase center of the probe antenna from the guidance angle processor output.

- vi) Angle Simulator - A guidance angle simulator will be needed to periodically test the performance of the guidance angle processor, due to the particularly tight performance requirements.

The guidance angle beam generator should be implemented in software for simplicity and applied to a modulator via a D/A converter thereby confirming that the amplitude detector and digitizer are working to performance requirements. It is proposed the modulation can be applied at the final IF frequency rather than at 5 GHz, as the down conversion should not affect the angle guidance accuracy. (This should be confirmed in a more detailed analysis for the particular down-converter selected.)

The controller should also be designed to allow the data to be gathered automatically and then analyze the measurements in non-real time. The operator will need to be informed of both GO/NO GO MLS operation to specification and display of actual performance on command. Where performance is marginal, the operator should be able to display the raw data as stored to aid in determining the reason and significance of the deviation.

It is proposed the Controller/Processor consist of a reliable, high performance micro-computer based on 16 or 32 bit technology (such as the 68000 or 8086), primarily to avoid early obsolescence, although having significant processing capacity and speed will assure the task is completed relatively quickly. The guidance angle processor may require a high speed multiplier, depending on the algorithm selected. Therefore, availability of a floating point co-processor could be advantageous.

While the recorder is not considered part of this study, it is worth commenting that 5 to 10 megabyte hard disk memories are currently available designed to be transported in the shock/vibration environment of a vehicle. Although operating the disk while the vehicle is moving is generally not recommended, this should not pose a severe restriction on usage. With this memory size, several programs can be stored while leaving significant space for data storage as well. This allows the previous day's run to be analyzed in greater detail at the operator's leisure.

5.2.3 MULTIPATH MEASUREMENT

In Section 4.2.4 of this report, the problems associated with measurement of multipath at an airport were described in some detail. It was concluded that, while a ground based test facility could not be used to make these measurements, the FAMAT Facility could be used to measure sidelobe performance, and then, by use of detailed airport maps and airphotos; the areas of worst case multipath could be predicted. It would be necessary to conduct airborne testing of multipath performance, but the testing could be concentrated on those areas where multipath was predicted to be significant.

5.2.3.1 Multipath Prediction

It is presumed the FAMAT SLL measurement will produce a plot of dynamic SLL versus approach angle and that, for most MLS equipment, the plot will approximate a straight line with a small variance as the angle changes. (The fact that this may not be true justifies the SLL measurements.)

First, it would be necessary to analyze airport maps and airphotos particularly noting height and position of buildings. Since the surface characteristics (roughness, etc.) of the building is also important, a photo or possibly a close-up inspection would be required. Once this information is gathered, two alternatives can be considered:

- a) Using experience and ray theory, estimate the location and magnitude of significant multipath.
- b) Using a multipath computer program, enter the building size, location, reflection characteristics, and run program.

The first technique is initially low cost but labour intensive. Lincoln Labs (Ref. 11) have produced a computer program which can apparently predict multipath with some degree of accuracy. Therefore, it is recommended this alternative be investigated to determine:

- i) Computer requirements (compatibility, etc.).
- ii) Data entry format and accuracy required.
- iii) Display output format (graphics or ?).
- iv) Cost to purchase.
- v) Cost to use.
- vi) Versatility.

5.2.3.2 Multipath Prevention

There are several alternative techniques which might be used to reduce the effect of multipath. It is beyond the scope of this study to discuss these in detail. However, a few alternatives are listed here for completeness:

- i) Select a MLS antenna with low SLL for particularly bad sites.
- ii) Use a non-symmetrical scanning MLS (if available).
- iii) Treat the side of buildings with non-reflective or diffusion coatings.
- iv) Install "fly-swatter" type diffraction fences (if possible).
- v) Issue aircraft warnings, particularly if area is well off runway centerline.
- vi) Plant small shrubs and grass in front of an Elevation antenna, since the prevention of ice formation, either on water or on top of snow in front of the antenna, is important. Bare asphalt or surfaces where standing water might gather must be avoided.

5.2.4 ESTIMATED COSTS OF A COMMISSIONING TEST FACILITY

The costs, both recurring and non-recurring, for a Commissioning Test Facility (CTF) are quite variable depending on two key factors, i.e.:

- i) Speed of measurement
- ii) Degree of automation

Combined, these two factors above could change the cost by an order of magnitude. Hence if a cost is to be estimated, a number of assumptions have to be made.

It is necessary to assume that two CTF's plus a spare will be needed. It is further assumed that measurement speed is not critical and that a measurement period of 10-20 minutes for SIP's and 3-6 hours for spatially dependent parameters is reasonable. A minimum two man operation, particularly for setting up a tower and for optical alignment, seems reasonable, unless a large number of airports have to be commissioned per month.

One technique which can be recommended is to provide a so called "quick-look" capability to provide a GO/NO GO test, but backed up by an extensive automated logging facility, so that the operator knows the equipment is operating while the tests are underway, but that after the tests are completed, detailed print-outs of test data can be requested and analyzed without the pressure of the field environment. This requires that the CTF include a recording device, preferably digital. Small amounts of data can be stored on a floppy disk or in semiconductor RAM, but for larger amounts, a magnetic tape or hard disk memory is essential. These recording devices all share a common concern, that is, vibration and sand and dust common to a transportable test facility are a problem for these essentially mechanical devices. It is recommended that the facility include such a recording unit, particularly designed to operate reliably in the vehicle environment.

With this philosophy in mind, the vehicle might be selected to maintain a quasi-laboratory environment, such as provided by a heated, air-conditioned van, possibly with a raised roof and windows for good visibility. (This approach would ensure doors would generally be closed, with temperatures fairly constant and minimal dust.)

5.2.4.1 INDOOR ELECTRONICS

Having defined the environment, the cost of the indoor mounted electronics can be estimated most easily by subdividing the costs into recurring and non-recurring costs. Table 5.1 lists the estimated recurring costs for the elements as defined in Figure 5.11, based on Option A.

Table 5.1 Recurring Costs

Module	Commercial or Custom	Recurring Cost	NRE Required	Remarks
Frequency Counter	HP5342A or equiv.	\$10K	N	
Modulation Analyzer	HP8901A or equiv.	\$14K	N	
Down-Converter and Detector	Custom (MITEQ)	17K + 8K	Y	
DPSK Demod	Custom	5K	Y	
Digitizer, Decoder and Data Register	Custom	8K	Y	2-8"x10" curcuit cards
Processor/Controller	VME-10 or equiv.	28K	Y	Software
Gain Calibrator	Custom	7½K + 4½K	Y	Marconi 2022 plus up-converter
Simulator Modulator	Custom	3K	Y	
Misc. (Rack, etc.)	-	20K	Y	
125K				

The Non-Recurring Engineering (NRE) costs to design and construct the custom hardware modules and to design and assemble the custom software is estimated as about \$350K (approx. 3 person years).

The Option B module costs are tabulated in Table 5.2.

Table 5.2 Option B Module Costs

Module	Commercial or Custom	Recurring Cost	NRE Required	Remarks
Power Meter	General Microwave 478	16K	N	
Spectrum Analyzer	Tektronix 492P	60K	N	
Frequency Counter	HP5345/56	15K	N	

5.2.4.2 OUTDOOR EQUIPMENT

Assuming that a suitable tower is available, the outdoor equipment consists of two items, an antenna and an antenna tracker.

The antenna cost was based on a flat plate phased array antenna utilizing a slotted waveguide concept. Based on pricing from Rantec, a cost of about \$5K is estimated for the antenna, with an additional \$3K for mounting.

The antenna optical tracker cost estimate is based on a theodolite (~ \$15K), a video tracker at about \$75K and a camera/manual zoom lens combination (~ \$5K). Non-Recurring Engineering would be required to package the system in a weatherproof container and calibrate the optical tracking system to achieve the desired accuracy, at an estimated cost of about \$60K.

A servo-controlled system with the required positional accuracy would likely increase the estimated cost by about another \$150K.

It should be noted the indoor/outdoor equipment costs must be considered budgetary only, since the scope of effort and detailed specifications will have to be defined before accurate estimates can be prepared.

5.2.5 OPTIONAL FEATURES

There are several optional features which would be desirable but not essential. Therefore, these features were excluded from consideration in the cost analysis of Section 5.4. Two features which might be considered most desirable are:

a) Additional Automation:

The obvious objective of additional automation would be to reduce the manpower requirements, for example, to one man. This could be accomplished but only at a rather high expense. The major need for additional manpower

would be during raising and lowering of the tower, moving the antenna up and down on the tower, and realigning the optical tracker during these maneuvers. This could be accomplished by providing a significant number of remote controls, mostly mechanical. Before such a feature should be added, a cost benefit analysis should be undertaken to determine the cost benefit trade-off. It would seem inadvisable to include this feature until some preliminary measurements have been completed on an airport. If considerable problems occur due to ground reflections, the manpower requirements could go up rather than down, if diffraction fences have to be moved for every measurement. Once a system has been established and performance limitations are quantified, the system could be upgraded to add automatic/remote control features.

b) DME-P Interface

A DME-P system will be provided with each MLS. It is probable that some of the tests appropriate to the DME could be performed using the computational and control power of the MLS Test Facility. As a minimum, the CTF should be designed so that a DME-P test set can be added with minimum difficulty at a later date. A study should be initiated to determine if existing DME test sets are suitable (it is unlikely), to define alternative test techniques, and to estimate costs of an optional system add-on.

The cost of incorporating the above two options into the CTF have not been included in this report.

5.3 PERIODIC TEST FACILITY

The Periodic Test Facility (PTF) is a ground test system which is required to periodically recheck the performance of an MLS without the high cost of repeating a Flight Inspection.

5.3.1 TEST PHILOSOPHY

The PTF should be functionally essentially identical to the Commissioning Test Facility, the major difference being that the probe antenna location is proposed to be fixed instead of moveable, thereby eliminating the need for an antenna tracking unit, and the electronics unit should be smaller and lighter.

It is assumed that the base locations for the PTF antenna mast will be permanently located, for example, with a poured concrete marker, so that the mast can be quickly erected and the measurements taken. However, the location accuracy requirements are quite severe, i.e., $\pm .0050$, which is equivalent to a location accuracy (in the direction of scan) of ± 6.1 mm at a distance of 70 meters. The mast can typically be quite short, i.e., about 3.7 meters long, equivalent to a 3° elevation angle at 70 meters for a MLS antenna with a phase center 2.5 meters above ground. The mast and mount can be made sufficiently sturdy that wind-induced vibration will be insignificant. However, the location accuracy requirement will necessitate the use of an optical alignment technique, such as a theodolite, to determine the actual location of the probe antenna phase center. Depending on the MLS physical design, it may be possible to alternatively provide a permanent sighting scope mount on the side of the MLS structure, to reduce the cost and effort necessary to adjust the alignment.

5.3.2 ANTENNA SUBSYSTEM

It is recommended that the test antenna be mounted at a distance of from 33 to 100 meters at a nominal elevation angle of 3° . (As the probe antenna is moved closer to the MLS, the mast will be shorter but the antenna positional accuracy becomes more stringent.) The test theoretically should be performed at several offset angles from the MLS selected randomly. However, this is both impractical and unnecessary, since the probability is that the MLS will either fail catastrophically or degrade gracefully due to component failure. Thus, a single measurement, preferably performed near runway centerline, will give a high degree of confidence that the MLS and the MLS field monitor are operating correctly. Increasing the number of locations will only increase the confidence slightly.

It is recommended that the same antenna proposed for the CTF be used for the same reasons, i.e., minimization of ground reflected multipath without excessive wind resistance. (Note that the tracking light is not required, however.)

Unfortunately, the Elevation MLS could be particularly difficult to assess because of ground reflected multipath, therefore, greater care will have to be taken during these measurements to ascertain if this condition exists. As mentioned previously, areas of water or level ice-covered snow can cause specular reflections, making accurate guidance angle error measurement very difficult. For this reason, it would be advisable to equip the mast with a method whereby the probe antenna can be raised or lowered 2 or 3 wavelengths and tests repeated at several heights in this range. If a large variance is seen in the guidance accuracy or radiated power, then more detailed testing is recommended. Fortunately, if this situation exists at the test location, it probably also exists at the aircraft and at the MLS field monitor and a Flight Inspection would be warranted.

5.3.3 RECEIVER/PROCESSOR

The Receiver/Processor is required to perform the same measurements as is required during commissioning tests. It is presumed, however, that there are likely to be several additional requirements, i.e.:

- Should be operable by one person
- Operator technical skill level requirements should be lower
- Should be smaller, lighter, and consume less power
- Should be less costly

These requirements only change the design a small amount, i.e.:

- Commercial equipment is undesirable from the size, weight, power aspect.
- Controller should be pre-programmed to carry out a specific series of tests.
- Display should be GO/No GO type with several progressively tighter limits.

- Recorder is even more essential since if the performance is marginal, a person with the necessary technical skills should be able to review the actual test data later in a laboratory environment.

With reference to the block diagram of Figure 5.11, the spectrum analyzer, Option A power meter, and modulation analyzer would be eliminated as options. A frequency counter, either Option A or B, would still be required. However, it would likely be designed as a custom-built unit.

5.3.4 PTF ESTIMATED COSTS

The cost of a PTF system is even more difficult to estimate because in quantities of 160, considerable cost savings over the CTF can be realized due to economies of scale. Depending on several major considerations such as environmental packaging requirements, power source limitations and recording capacity, a price objective of \$50 to \$100K does not seem unreasonable. This price is considerably lower because much of the technology is incorporated into software with inherently lower recurring costs than if commercial off-the-shelf hardware were used. Depending on the similarity to the CTF software previously developed, some NRE should be budgetted to produce custom software.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This section of the report provides the recommendations and conclusions as contained within this report in a summary form. The recommendations and conclusions are tabulated under four headings, i.e.:

- 1) MLS Design Requirements
- 2) First Article MLS Antenna Test Facility
- 3) Commissioning Test Facility
- 4) Periodic Test Facility

6.1 MLS DESIGN REQUIREMENTS

The objective of the recommendations contained in this subsection is to define additional requirements that should be placed on the design and manufacture of an MLS beyond that required by the ICAO SARPS, with the objective of both improving MLS performance and making the MLS easier to test. It should be noted that the test facilities description contained in the report does not depend inherently on these recommendations being followed; however, the cost of the particular facility may be higher if they are not. (Note that SOP stands for Statement of Problem and RS stands for Recommended Solution.)

- a) SOP: ICAO AWOP-10 recommends that the MLS data format be changed significantly.
RS: If the MLS data transmission configuration is variable, the MLS should transmit a key word which identifies which data format is being used at that site. This will assist both the airport user and the test facility user.
- b) SOP: Alignment of the MLS antenna phase center with the probe antenna is essential, particularly for accurate probe antenna tracking.
RS: The phase center of the MLS antenna should be marked clearly on the radome surface. It is also desirable that the antenna radome structure include a bracket properly aligned with the internal antenna to aid in boresighting the antenna.

c) SOP: Multipath signals will cause the MLS accuracy to deteriorate both for the airport user and the test facility user.

RS: The MLS AZ antenna radiation pattern at low elevation angles (horizon and below) should be controlled, preferably by means of Transport Canada defining a tighter specification than that required by ICAO. Similarly, the MLS EL antenna radiation pattern should be controlled in the non-scan plane to restrict radiation outside of the proportional coverage area.

d) SOP: The frequency of a pulse/phase modulated signal is difficult to measure accurately at a reasonable cost.

RS: If possible, the MLS should include a nominal 5 GHz CW output signal sample prior to modulation, plus the manufacturer should confirm that the modulation process does not change the frequency of operation (both long and short term stability are important).

e) SOP: The effect of multipath on guidance angle performance depends strongly on the particular airport, in particular hanger/building locations and ground characteristics in front of the EL antenna. It may well be impossible to design a MLS which can meet the requirements at all airports, even with the best intentions.

RS: The MLS manufacturer should be required to measure sidelobe level performance to meet a Transport Canada defined specification (the method of measurement should be defined as well).

In conjunction with this specification, Transport Canada should be encouraged to investigate multipath prevention at troublesome airports, for example, by planting of small shrubs and grass in front of the antennas (EL in particular).

- f) SOP: In order to provide an accurate measurement of sidelobe level, the EL antenna should be operated and tested on its "side" (i.e., rotated 90°) at an antenna test facility.
- RS: The MLS manufacturer should be required to state if the EL system can be operated on its "side" (temporarily) and if performance will be degraded in any way due to this mounting technique.
- g) SOP: Some radome materials are more resistant to formation of ice on the surface than others.
- RS: The MLS manufacturer should be asked to test a radome material sample to determine its ice adhesion properties.
- h) SOP: The MLS performance accuracy may be affected by wind-induced vibration.
- RS: The MLS manufacturer should be asked to either test MLS performance under windy conditions, or alternatively, to test the vibration properties of the MLS antenna and structure to determine the resonant frequencies of the overall structure and the radiating elements so that radiation tests could be performed.
- i) SOP: The MLS antenna may be sensitive to humidity effects.
- RS: The MLS manufacturer should be asked to test hermeticity of the radome enclosure if the enclosure is stated to be hermetically sealed.

6.2 FIRST ARTICLE MLS ANTENNA TEST FACILITY

The purpose of a First Article MLS Antenna Test Facility is to provide a location where accurate sidelobe level testing and controlled environmental testing can be performed without multipath interference. The following recommendations apply to this facility:

- a) SOP: Multipath signals can cause guidance angle errors and can interfere with measurement of sidelobe level.
- RS: A low multipath facility (with both receive and transmit antennas located well above ground level) is needed, with a high positional accuracy ($\pm 0.005^\circ$) turntable.
- b) SOP: Ground reflected multipath is a particularly onerous problem for the EL system.
- RS: The EL MLS should be tested "tipped" on its side so the scanning plane is horizontal, thereby reducing the effect of ground reflected interference.
- c) SOP: The FAA proposed technique for measuring sidelobe level is somewhat complex, and requires a calibrated MLS Receiver to measure results.
- RS: The alternate method of sampling and digitizing the sidelobe signals and then calculating the dynamic sidelobe level should be implemented and tested using an existing MLS.
- d) SOP: Environment tests on the MLS antenna performance are very difficult to perform at an airport site.
- RS: The FAMAT facility can be used to measure temperature sensitivity of the MLS antenna by constructing a small, radio-transparent structure around the MLS and applying heating/cooling.

The FAMAT facility can be used to determine if a particular radome is sensitive to simulated rain, and how the system performance is degraded by the "rain".

If the MLS radome is not hermetically sealed, then humid air could be circulated through the radome. Each manufacturer should be requested to advise as to how this might be done without adversely affecting the performance (other than humidity effects).

A method of testing the susceptibility of MLS to wind-induced vibration requires further study. Due to the proprietary aspect of each structure, each manufacturer will have to be consulted as to how this might best be done, since it does not seem practical to control wind velocity at the FAMAT site.

- e) SOF: Degraded performance due to soft-failures in the antenna will have to be proved to be within acceptable limits.
- RS: The FAMAT facility can be used to quantitatively assess performance under "soft-failure" conditions (assuming the manufacturer defines how the failures are to be simulated).

6.3 COMMISSIONING TEST FACILITY

A CTF is required to confirm that an installed MLS meets all of the ICAO performance requirements. It is recommended that a ground test facility be used to accomplish this testing primarily because the recurring costs of flight testing will be higher than ground testing. Some flight testing will also be required, however, this can be minimized by analyzing the airport for multipath reflectors and limiting testing to those areas in the coverage volume where multipath interference is expected.

The CTF should be implemented using the following recommendations to achieve the required performance:

- a) SOP: Far field testing is expensive and near field testing is impractical.
- RS: The CTF testing should take place in the quasi-near field at a distance of 30 to 45 meters in front of the MLS at heights of 0 to 15 meters.

- b) SOP: The cost of an antenna tracker unit is difficult to estimate without experimental test data on the actual tower motion under windy conditions.

RS: An erectible tower and theodolite should be rented and the amount of wind-induced tower motion measured under various wind conditions.

- c) SOP: Due to the wide variety of MLS site conditions that can be expected, ground reflections may vary over a wide range, making accurate guidance angle measurements difficult.

RS: The antenna should be mounted on the tower such that it can be easily moved over about 1 meter vertical distance to determine the multipath severity.

If the multipath is severe, a diffraction fence should be available to aid in reduction of the reflection.

- d) SOP: The probe antenna should be large to reduce multipath effects and yet be sufficiently small to avoid significant wind resistance.

RS: A rectangular array antenna about 60 cm. square (based on either a slotted waveguide structure or a microstrip patch array), rigidly constructed to avoid bending, and designed to accommodate a high intensity lap at its phase center is recommended.

- e) SOP: The location of the antenna phase center is required to be tracked with an angular accuracy of $\pm 0.005^\circ$ w.r.t. the MLS antenna phase centerline, including harmonic motion with frequencies of up to 1.5 Hz.

RS: An optical tracker is suggested, either manual or automatic. (An experimental evaluation of the viability of manual tracking will be required before it can be recommended.) An automatic tracker based on a video tracker to augment a theodolite, or alternatively a servo-controlled tracker are proposed for consideration.

f) SOP: The Receiver/Processor can be based on either commercial test equipment or custom designed circuitry.

RS: While the non-recurring cost of custom designed equipment is higher, the custom design is more flexible, offers faster execution time, and is smaller and lighter. For a quantity of two, the costs are estimated to be similar. Hence the custom design is recommended (particularly if the software is the property of Transport Canada and can be changed easily). A mixture of commercial/custom equipment could well be even more cost effective.

Since the PTF (discussed in Section 6.3) is likely to be based on this design, size and weight should be considered.

g) SOP: If custom designed electronics are included in the CTF, calibration is important, considering the accuracy requirements.

RS: The guidance angle measurement accuracy is crucial and difficult to meet. Hence, an accurate technique of confirming the accuracy repeatability is essential. A guidance angle simulator must be designed and built, since no commercial equivalent could be located. This simulator may be built-in or separately packaged.

A method of confirming the accuracy of power measurements is also required, either built-in or periodically testable with the necessary interim stability.

h) SOP: The analysis of test results often takes longer than the measurements.

RS: The CTF should include a data recorder which records the test data as well as the GO/NO GO limits, test parameters, test locations, etc.

i) SOP: The guidance angle processor is required to have a beam center finding accuracy of $\pm 0.005^\circ$, which is considerably better than that required of off-the-shelf MLS Receivers. Therefore, a commercial MLS Receiver may not be adequate to perform the test.

RS: Since a commercial MLS Receiver might serve as the core of a lower cost CTF, it is recommended that several commercial receivers be tested to ascertain if the required accuracy can be attained.

j) SOP: Multipath testing over the entire coverage area would be time consuming, expensive and possibly interfere with normal airport usage.

RS: An analysis of the airport profile using maps and photos should be undertaken to define the areas where multipath is expected to be severe. This can be done manually. However, it is recommended that the availability of a computer program to assist in this analysis be investigated.

k) SOP: Each MLS is anticipated to be supplied with a DME-P. This study did not include consideration of the requirements for DME-P testing.

RS: The addition of a DME-P was not studied. However, the Processor/Controller should be designed with excess capacity to handle this feature when it becomes available.

Note that DME-P testing is expected to be difficult due to the accuracy requirements. Therefore, a study of the DME-P test facility requirements is also suggested.

6.3 PERIODIC TEST FACILITY

A Periodic Test Facility is required to confirm that the MLS and its associated field monitor are operating correctly and to confirm that the performance is not degraded to the point where it is marginal.

It is recommended that the PTF be functionally similar to the CTF previously discussed, therefore, all recommendations also apply to the PTF. There are some exceptions where the PTF is anticipated to be different. Therefore, these additional requirements are discussed below.

- a) SOP: The PTF testing should be performed more quickly than the commissioning facility tests.

RS: It is recommended that the tests be performed in the quasi-near field (33 to 70 meters in front of the MLS) using a rigid tower mounted in a single pre-defined location with the probe antenna at a nominal 3° elevation angle. A second location should also be provided at a different offset angle, however, this location would only be tested occasionally to maintain confidence at a high level.

An optical tracker is not anticipated to be required due to the rigidity of the mast, therefore, a tracker unit should not be required. A theodolite or similar sighting device can be used to locate the mean antenna location to the required accuracy.

- b) SOP: Multipath, particularly for the EL antenna, may be a problem at some sites.

RS: The probe antenna should be vertically movable over a distance of 5-10 cm. to determine the extent of multipath prior to a measurement.

- c) SOP: The Receiver/Processor Unit should be smaller and lighter to ease transportation problems.

RS: The Receiver/Processor does not require the degree of flexibility necessary in the CTF for testing at many locations. In addition, the data storage requirements are smaller for the same reason. As a result, size and weight should be reduced.

A commercial frequency counter can be replaced with a custom designed, smaller unit and it is proposed that the short term frequency stability test is unnecessary since this parameter is unlikely to significantly affect MLS performance.

7.0 REFERENCES

- 1 International Standards and Recommended Practices (SARPS),
Aeronautical Communications, Annex 10, ICAO, Vol. 1, Jul. 1972,
Section 3.11, MLS Characteristics.
- 2 All Weather Operations Panel, Tenth Meeting (AWOP-10), Agenda
Item 2-MLS, ICAO, Montreal, Canada, Sept. 1984.
- 3 Telecommunications Systems Engineering, W. Lindsay & M. Simon,
Prentice Hall, 1973.
- 4 Laser Based Near Field Probe Position Measurement System,
W.A. Harmening, Microwave Journal, Oct. 1983 (p-91).
- 5 Antenna Engineering Handbook, Jasik, McGraw Hill, 1984.
- 6 IEEE Standard Test Procedures for Antennas, IEEE, 1979.
- 7 Numerical Techniques,
- 8 Detection, Estimation and Modulation Theory, Part I, H.L. Vantrees,
Wiley, 1969
- 9 Federal Aviation Administration - U.S.A., MLS Ground Equipment
Requirements, FAA-E-2721/1A, Oct. 83.
- 10 Time Reference MLS Multipath Control Techniques, Kelly, Navigation,
Vol. 23, No. 1, Spring 1976.
- 11 MLS Multipath Studies, Evan, Dolimar, Shnidman & Bruchsted, Lincoln
Labs, Feb. 1980.
- 12 MLS, A New International Standard, Redlien & Kelly, Adv. Electronics
and Electron Physics, Vol. 57, 1981.
- 13 Radar Handbook, M. Skolnik, McGraw Hill, 1970, Section 14, Radomes.
- 14 Physical Limitations on Antennas, J. Ruze, Tech. Report #248,
Research Lab, MIT, October 1952.

APPENDIX ACALCULATION OF ANGLE ACCURACY

A.1 INTRODUCTION

The angle guidance accuracies tabulated in Tables 3.16, 3.17 and 3.18 can be expressed as explicit functions of the azimuth angle ϕ , the elevation angle θ and the radial distance r from the antenna phase center. These closed formed expressions are given below:

A.2 AZIMUTH COVERAGE

$$PFN(r, \phi, \theta) = \begin{cases} \left(\frac{r}{37} + 1\right) \left(\frac{\phi}{80} + 1\right) x ; 0.9^\circ \leq \theta \leq 9^\circ \\ \left(\frac{r}{37} + 1\right) \left(\frac{\phi}{40} + 1\right) \left(\frac{\theta}{6} - \frac{1}{2}\right) x ; 9^\circ \leq \theta \leq 15^\circ \end{cases}$$

$$0 \leq r \leq 37 \text{ km.}$$

$$|\phi| \leq 40^\circ$$

r is in km.

ϕ is in degrees

θ is in degrees

x is the error limit at threshold

$$PFE(r, \phi, \theta) = PFN(r, \phi, \theta)$$

$$CMN(r, \phi, \theta) = \left(\frac{r}{61.7} + 1\right) \left(\frac{\phi}{133.3} + 1\right) x$$

$$r \leq 18.5 \text{ km.}$$

$$|\phi| \leq 40^\circ$$

A.3 BACK AZIMUTH

$$PFN(r, \phi, \theta) = \begin{cases} \left(\frac{r}{9.27} + 1\right) \left(\frac{\phi}{40} + 1\right) x & ; 0.9^\circ \leq \theta \leq 9^\circ \\ \left(\frac{r}{9.27} + 1\right) \left(\frac{\phi}{40} + 1\right) \left(\frac{\theta}{6} - \frac{1}{2}\right) x & ; 9^\circ \leq \theta \leq 15^\circ \end{cases}$$

$$r \leq 9.27 \text{ km.}$$

$$|\phi| \leq 20^\circ$$

$$PFE(r, \phi, \theta) = PFN(r, \phi, \theta)$$

$$CMN(r, \phi, \theta) = \left(\frac{r}{30.9} + 1\right) \left(\frac{\phi}{66.7} + 1\right) x$$

$$r \leq 9.27 \text{ km.}$$

$$|\phi| \leq 20^\circ$$

A.4 ELEVATION

$$PFE(r, \phi, \theta) = \left[\frac{(0.2 - x)r}{37} + x\right] \left(\frac{\phi}{133.3} + 1\right) \left(\frac{\theta - \text{MGP}}{15 - \text{MGP}} + 1\right)$$

$$\text{MGP} \leq \theta \leq 15^\circ$$

MGP = Minimum Glide Path

$$r \leq 37 \text{ km.}$$

$$\text{MGP} \leq 2^\circ$$

$$|\phi| \leq 40^\circ$$

$$PFE(r, \phi, \theta) = PFN(r, \phi, \theta)$$

$$CMN(r, \phi, \theta) = \left(\frac{r}{61.7} + 1\right) \left(\frac{\phi}{133.3} + 1\right) \left(\frac{\theta - \text{MGP}}{15 - \text{MGP}} + 1\right) x$$

$$\text{for } 0.9^\circ \leq \theta \leq 0.6 \text{ MGP}$$

$$PFE(r, \phi, \theta) = \left[\frac{(0.2 - x)r}{37} + x\right] \left(\frac{\theta}{133.3} + 1\right) \left[5\left(\frac{0.6 \text{ MGP} - \theta}{0.6 \text{ MGP} - .09}\right) + 1\right] \theta$$

$$0.9^\circ \leq \theta \leq 0.6 \text{ MGP}$$

$$CMN(r, \phi, \theta) = \left(\frac{r}{61.7} + 1\right) \left(\frac{\phi}{133.3} + 1\right) \left[5\left(\frac{0.6 \text{ MGP} - \theta}{0.6 \text{ MGP} - 0.9}\right) + 1\right] \theta$$

APPENDIX BCALCULATION OF QUASI-NEAR FIELD EFFECTS ON ARRAY PATTERN ACCURACY

B.1 INTRODUCTION

This appendix describes the derivation of the equation used to calculate the quasi-near field pattern of an array antenna.

For a general linear array of equally spaced elements the relative amplitude of the radiated field strength is given by:

$$E = a_0 e^{j\alpha_0} + a_1 e^{j\psi + j\alpha_1} + a_2 e^{j2\psi + j\alpha_2} + \dots$$

$$\text{where } \psi = \beta d \cos \phi + \alpha, \quad \beta = \frac{2\pi}{\lambda}$$

In this expression, d is the spacing between elements. The coefficients a_0, a_1, a_2 , etc. are proportional to the current amplitudes in the respective elements. α is the progressive phase shift from left to right; α_1, α_2 , etc. are deviations from this progressive phase shift between elements.

B.2 QUASI-NEAR FIELD CALCULATIONS

For distances where the following equation is true:

$$R_S < \frac{2 \times D^2}{\lambda}$$

(where D is the overall width of the antenna and

λ is the wavelength) then R_I must be evaluated for each element and the difference in path length ($R_I - R_S$) calculated for each element as illustrated in Figures B.1 and B.2. (Note that R_S equals the distance from the probe antenna to the array centre and d equals the inter-element spacing.)

When the probe antenna is very far from the array,

$$R_S > \frac{2 \times D^2}{\lambda}$$

Then the phase path difference between adjacent elements is constant.

The phase path difference between the array center and the centre of the I th element when R_S is very large is given by:

$$\phi_{I-C} = \frac{2\pi}{\lambda} \left(I - \frac{1}{2} \right) d \sin \theta$$

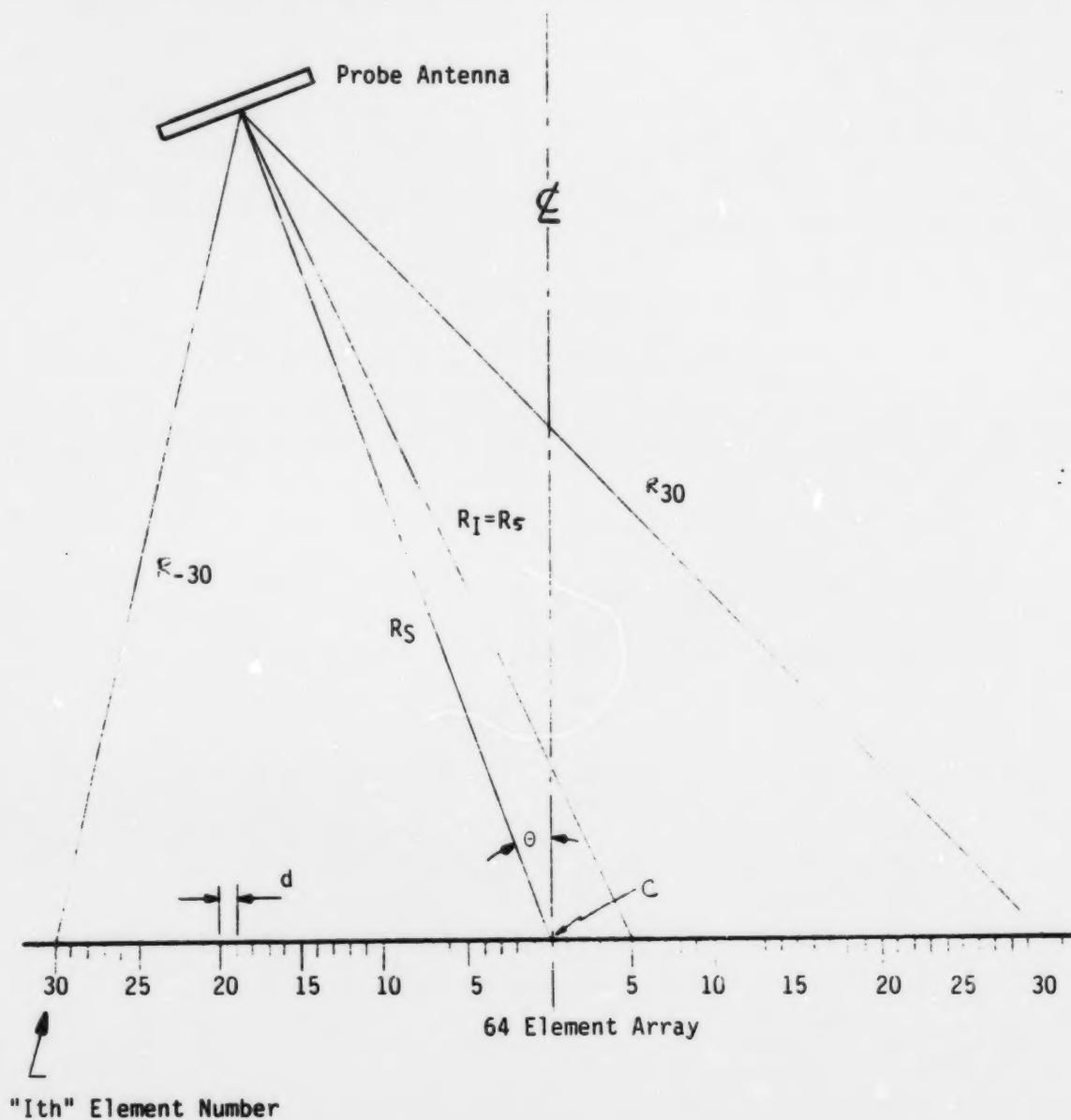


Figure B.1 Quasi-Near Field Model

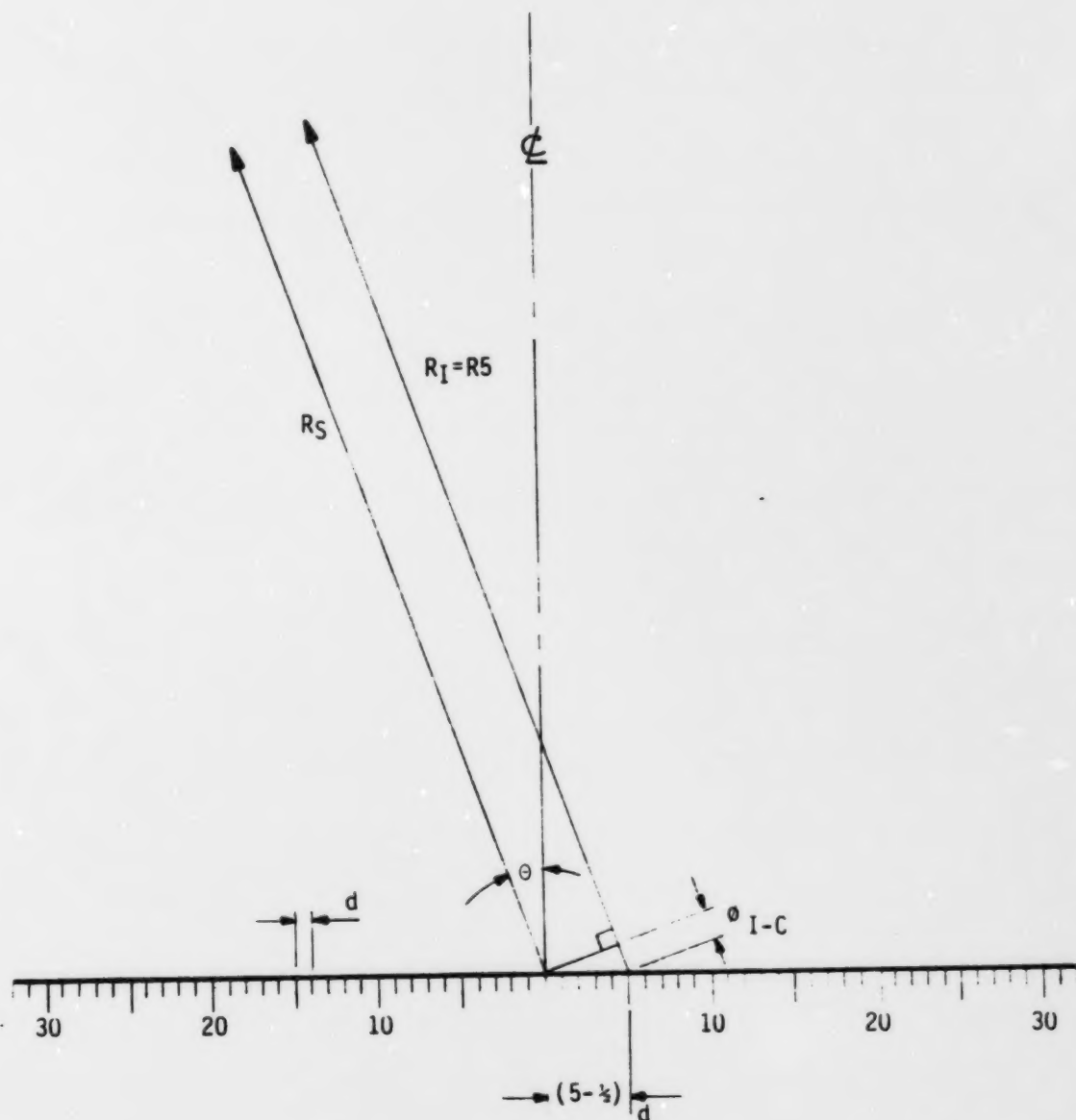


Figure B.2 Far-Field Model

This is the phase path difference usually used in calculating field radiation patterns of arrays with uniform spacing.

When the probe antenna is located R_S feet away from the centerline of the antenna, the difference in phase path length between each element and the probe horn can be calculated using the Law of Cosines.

$$R_I = \sqrt{R_S^2 + [(I - \frac{1}{2})d]^2 - 2 R_S (I - \frac{1}{2})d \cos (\theta + 90^\circ)}$$

where:

R_I = center to center distance between probe antenna and array

$R_I - R_S$ = Path length difference between Array center and Ith element

ϕ_{I-C} = Phase Difference between Array Center and Ith element

$$\phi_{I-C} = \frac{2\pi}{\lambda} (R_I - R_S)$$

APPENDIX CCALCULATION OF RECEIVED POWER

C.1 RECEIVED POWER

The power P_R at the receive antenna is given by:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi r)^2} \quad (A1)$$

in which

P_T = transmit power

G_T = gain of transmit antenna

G_R = gain of receive antenna

λ = wavelength

r = distance of receive antenna from transmit antenna

The power density S of the received signal is given by:

$$S = \frac{P_T G_T}{4\pi r^2} \quad (A2)$$

Expressing (A1) and A2) in terms of decibels:

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T(\text{dB}) + G_R(\text{dB}) - 20 \log r (\text{km.}) - 20 \log f (\text{MHz}) - 32.44$$

$$S(\text{dBW/m}^2) = P_T(\text{dBm}) + G_T(\text{dB}) - 20 \log r (\text{meters}) - 30 - 10 \log 4\pi$$

$$= P_T(\text{dBm}) + G_T(\text{dB}) - 20 \log r (\text{meters}) - 41.0 \quad (A3)$$

Furthermore,

$$P_R = \frac{S \cdot G_R \lambda^2}{4\pi}$$

or $P_R(\text{dBm}) = S(\text{dBW/m}^2) + G_R(\text{dB}) - 5.5$ (A4)

According to the ICAO specification

$$S \leq -82 \text{ dBW/m}^2 \text{ at } 37 \text{ km.}$$

From (A3), one obtains

$$P_T + G_T \leq 50 \text{ dB} \quad (\text{A5})$$

Using (A5) in (A3) with $r=40 \text{ m}$.

$$\begin{aligned} S(140 \text{ meters}) &> 50.4 - 41 - 20 \log 40 \\ &> -22.7 \text{ dBW/m}^2 \end{aligned}$$

Finally, using (A4)

$$P_R(\text{dBm}) > -22.7 - 5.5 + G_R(\text{dB})$$

Assuming a receive antenna gain of 10 dB to 15 dB, the receive power would be -13 dBm to -18 dBm.

APPENDIX DDETAILED DESCRIPTION OF EQUIPMENT REQUIREMENTS
FOR A DFL TEST FACILITY

D.1 INTRODUCTION

This appendix describes the equipment necessary to adapt the David Florid Labs (DFL) facility to meet the Transport Canada requirement for a First Article MLS Antenna Test Facility.

D.2 FACILITY DESCRIPTION

Figure D.1 illustrates the outdoor configuration of the DFL test facility configured to test a MLS antenna. Figure D.2 shows the equipment layout in each of the locations, i.e., the Roof Facility, the Control Room, the Tower Building and the Tower Platform. Figure D.3 illustrates a more detailed block diagram of the Receiver/Processor Unit to be located in the Tower Building.

A list of required equipment is provided in Table D.1, including a definition of all equipment and facilities provided by DFL for the MLS measurement task.

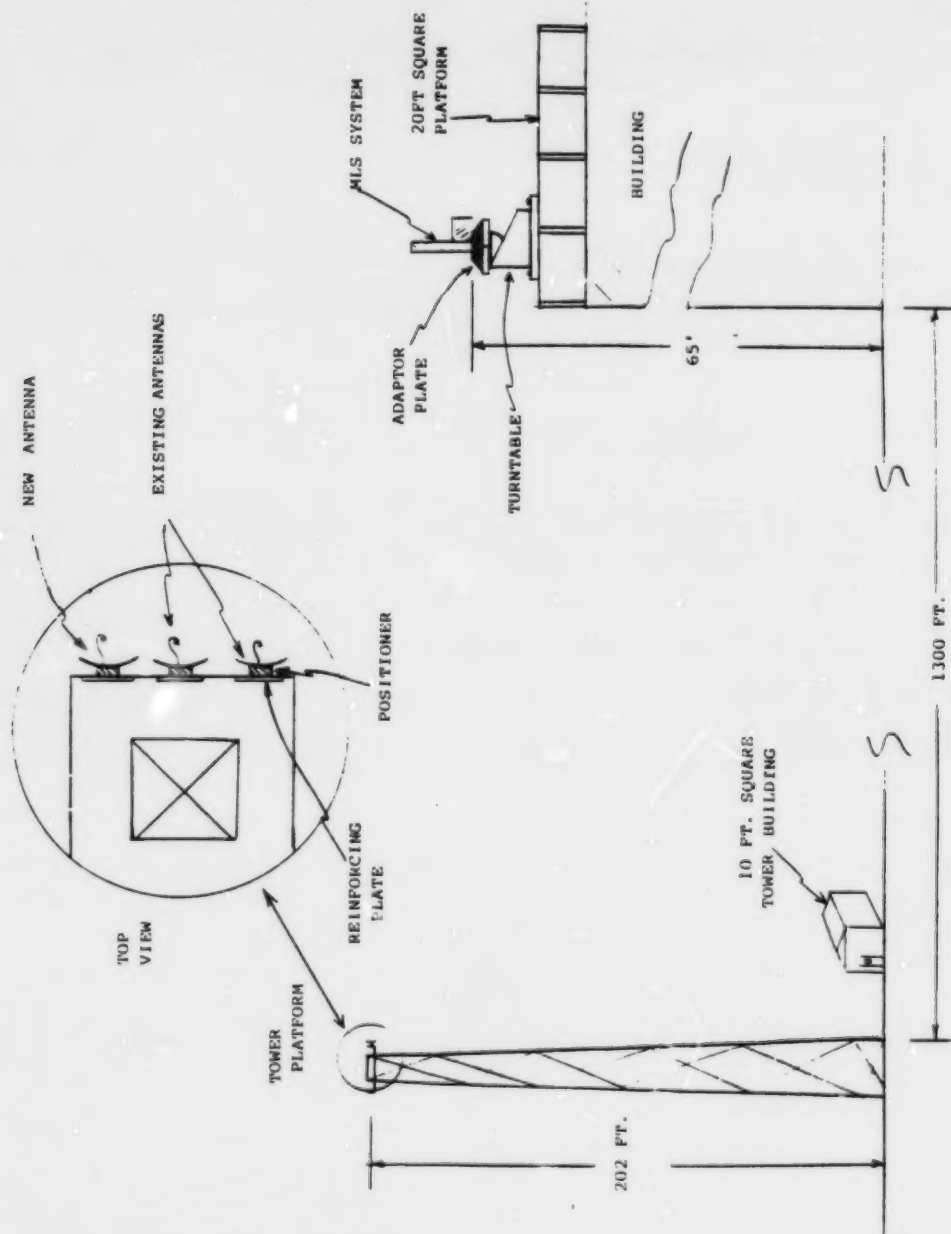
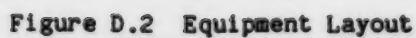


Figure D.1 DFL Antenna Range Facility



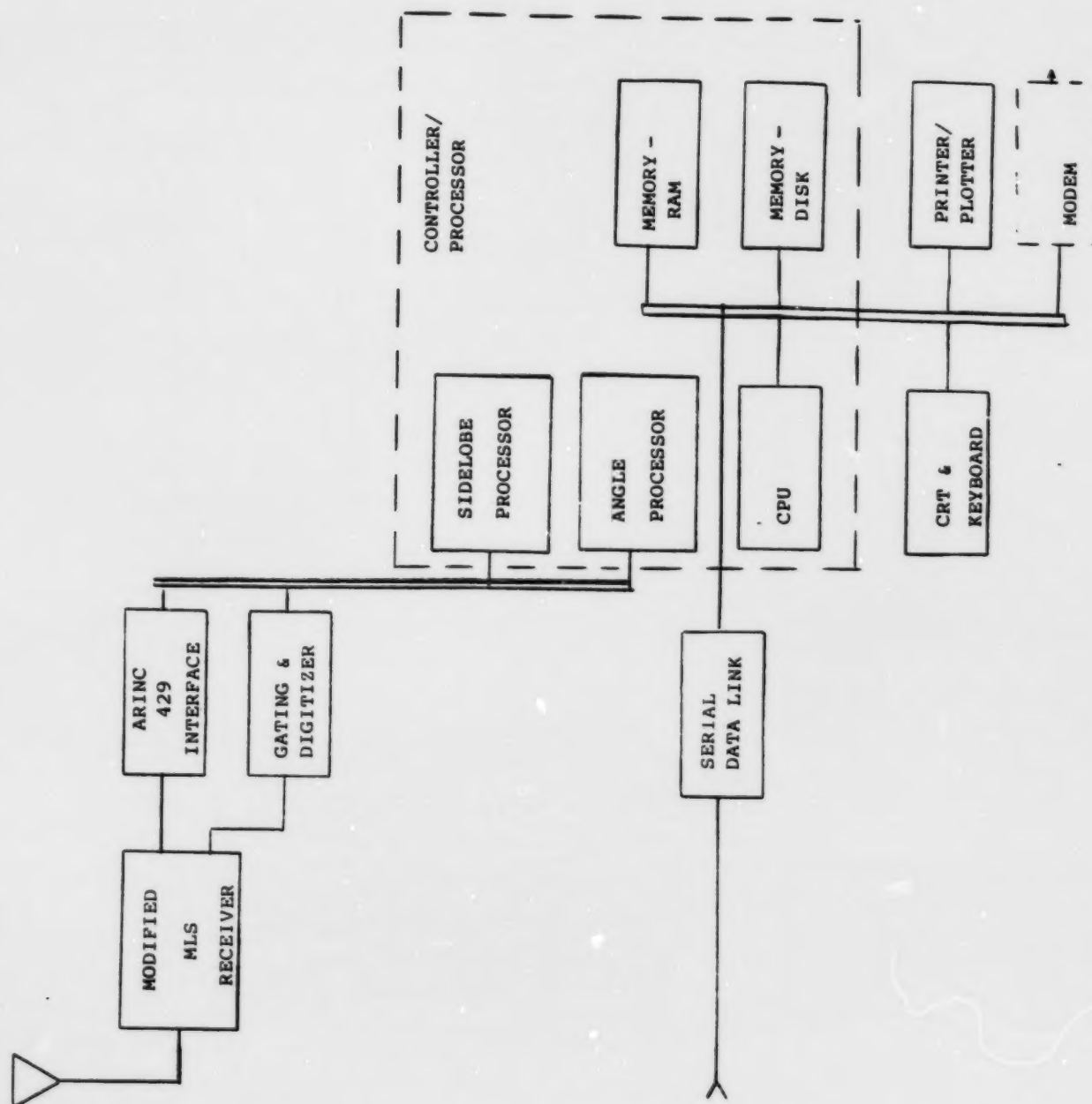


Figure D.3 Receiver and Processor Unit Block Diagram

Table D.1

Equipment	Supplied By	Description/Remarks
MLS System	TC	
Turntable Adaptor	TC	- Azimuth - normal mount - Elevation - "tipped" 90° mount
Turntable w/synchro	DFL	Scientific Atlanta 53300A or equivalent (30,000 lbs, $\pm 0.05^\circ$ EL, $\pm 0.030^\circ$ AZ), with rain shield for optical encoder
Optical Encoder	TC	BE1 model 5V682HB or equivalent, $\pm 0.005^\circ$ accuracy, hollow shaft, -40° to +60°C (Azimuth only)
Synchro Display	DFL	Scientific Atlanta model 1844 or equivalent (required for elevation position data)
Control Unit Local	DFL	Scientific Atlanta model 4116A or equivalent
Parallel-to-Serial Converter	TC	Converts optical encoder output to serial data for transmission to tower site
Telephone/Intercom	DFL	Allows conversation between control room and tower building
Cable to tower building	DFL	24 pair #8 wire
Antenna	TC	6 ft. diameter Parabolic dish, Andrews model PL 6-44E or equivalent, (single polarized, 2.5° BW)
Antenna Mounting Adaptor	DFL	Custom built
Antenna Positioner (manual rotation)	DFL	Scientific Atlanta model 56810 or equivalent
Antenna polarization positioner (optional)	DFL	Scientific Atlanta model 56260A or equivalent with a 1844 or equivalent display
Coaxial cable	TC	300 ft. $\frac{1}{2}$ " HELIAX
Tower Building	DFL	10 ft. x 10 ft. building, heated and A/C
DC Control Unit (Remote)	DFL	Scientific Atlanta model 4116A or equivalent
Serial Data Interface	TC	Converts serial data into format suitable for computer
Modified MLS Receiver	TC	Modified to provide auxiliary output
Gating and Digitizer Processor/Controller	TC	Motorola VME-10 CPU or equivalent with 1MB RAM, 10 MB hard-disk, keyboard and CRT with custom software
Telephone Intercom	DFL	To communicate with control room
Temperature Housing w/Thermocouples	TC	To be constructed using RF transparent styrofoam to surround antenna